VOLUME 25 FEBRUARY, 1937 NUMBER 2

PROCEEDINGS
of
The Institute of Radio Engineers

Application Blank for Associate Membership on Page XI

Institute of Radio Engineers Forthcoming Meetings

CLEVELAND SECTION
February 25, 1937

DETROIT SECTION
February 19, 1937

LOS ANGELES SECTION
February 16, 1937

NEW YORK MEETING
February 3, 1937
March 3, 1937

PHILADELPHIA SECTION
February 4, 1937
March 4, 1937

TORONTO SECTION
February 8, 1937
February 22, 1937

WASHINGTON SECTION
February 8, 1937

Annual Meeting of the Board of Directors

On January 6, 1937, there was held in the Institute office a meeting of the 1936 Board of Directors to confirm the minutes of the December 2, 1936, meeting. After this action, Messrs. Batcheller and Wilson, whose terms expired, departed and the annual meeting of the new Board of Directors was called to order by President Beverage. Those present were: Ralph Bown, Alfred N. Goldsmith, Virgil M. Graham, Alan Hazeltine, Haraden Pratt, H. M. Turner, and H. P. Westman, secretary.

Melville Eastham was reappointed treasurer to serve for 1937 and H. P. Westman was reappointed secretary for the year.

In 1936, Mr. Beverage was elected to serve as a director for 1936–1938. Subsequently he was elected president for 1937 and will continue on the Board as a director through 1938 and 1939 as past president. Because of this overlap, he submitted his resignation as an elected director leaving that office vacant for 1937 and 1938. This vacancy is filled by Board appointment. The constitution requires the appointment by the Board of five directors to serve one-year terms. The vacancy due to the resignation of President Beverage as an elected director made essential the appointment of six directors to serve in 1937. Those appointed were: T. A. M. Craven, L. C. F. Horle, C. M. Jansky, Jr., C. B. Jolliffe, A. F. Murray, and B. J. Thompson.

Action was taken on a partial list of committee personnel. The final action will be taken to complete these lists at the February meeting of the Board of Directors and the lists will appear in the 1937 YEAR BOOK which will be published in March.

F. E. Terman was transferred to the grade of Fellow and J. H. Gillies was admitted to the grade of Member. The following were transferred to the grade of Member: M. A. Acheson, H. E. Ackman, R. M. Bowie, W. A. Ford, D. E. Foster, R. R. Hoffman, M. I. Kahl, R. N. Palmer, A. P. Richards, L. E. West, and M. D. Wilson. Fifty applications for Associate, five for Junior, and twenty-two for Student membership were approved.

The Secretary reported that in accordance with authorization given at a previous meeting, the services of J. D. Crawford were obtained as advertising manager.

A part-time office boy has been employed to replace in part the services of a full-time clerk whose resignation was recently received.

As was done in 1936, the payment of a new entrance fee by delinquent members desirous of becoming reinstated was waived. This will apply to reinstatements during 1937 but there is no assurance that the policy will be continued beyond the end of the year.

A balanced budget for 1937 has been approved. An estimated increase in receipts is reflected in proposed expenditures among other things for convention, office equipment, PROCEEDINGS, standards reports, YEAR BOOK, and staff salary increases equal to the reductions made in 1932.

H. M. Turner was designated the Institute's representative on a subgroup on Communication Symbols operating under the Sectional Committee on Graphical Symbols and Abbreviations for use on Drawings.

The paid membership at the end of 1936 was reported as 5195 compared with 4423 at the end of 1935, an increase of about seventeen per cent.

Joint Meeting of the Institute and the American Section of the International Scientific Radio Union

The annual joint meeting of the Institute of Radio Engineers and the American Section of the International Scientific Radio Union will be held in Washington, D. C., on April 30, 1937. This all-day meeting is an important feature of the week which attracts to Washington every year an increasingly large number of scientists and scientific societies. Papers on the more fundamental and scientific aspects of radio will be presented. Titles of papers offered for this program should be submitted immediately. It is desirable but not necessary that abstracts be submitted with the titles. An abstract will be required by March 20. The program, with abstracts, will be mailed to those interested before the meeting. Correspondence should be addressed to Mr. S. S. Kirby, National Bureau of Standards, Washington, D.C.

Committee Work

NEW YORK PROGRAM COMMITTEE

A meeting of the New York Program Committee was held in the Institute office on December 20, 1936, and was attended by Haraden Pratt, chairman; R. R. Beal, G. C. Connor, Alan Hazeltine, Keith Henney, R. A. Heising, George Lewis, H. F. Olson, L. G. Pacent, J. C. Schelleng, B. J. Thompson, and H. P. Westman, secretary.

The meeting was devoted to the editing of five technical committee

reports which collectively comprise the review of radio activities for 1936 which is published elsewhere in this issue.

Standards Committee

The Standards Committee met in the Institute office on December 22 and those present were L. C. F. Horle, chairman; J. Blanchard (representing William Wilson), H. F. Olson, J. C. Schelleng, B. J. Thompson, H. M. Turner, H. A. Wheeler, and H. P. Westman, secretary.

The report on definitions of the Technical Committee on Electroacoustics was reviewed. A number of items were referred to the committee for further consideration.

Television and Facsimile Committee

Two meetings of the Television and Facsimile Committee were held in the Institute office, the first on November 20 and the second on December 14. The meetings were devoted to the preparation of a review of the field for 1936 for presentation at the annual meeting of the Institute. The November meeting was attended by J. V. L. Hogan, chairman; F. J. Bingley, (representing A. F. Murray), C. W. Horn, E. F. Kingsbury, H. M. Lewis, R. J. Wise (representing J. W. Milnor), and H. P. Westman, secretary. The meeting held in December was attended by J. V. L. Hogan, chairman; J. W. Arnold, E. W. Engstrom, C. W. Horn, H. M. Lewis, Henry Sheve (representing R. H. Manson), J. E. Young, and H. P. Westman, secretary.

Institute Meetings

Buffalo-Niagara Section

A meeting of the Buffalo-Niagara Section was held on December 9 at the University of Buffalo and attended by twenty-seven. G. C. Crom, chairman, presided.

A paper on "Vibrators and Their Transformers" was presented by C. T. Wallis of Delco Applicance Corporation. He discussed the various methods of obtaining B supply for automotive receivers. Among these was the vibrator which has been used for years by the telephone industry as a pole changer.

Characteristic curves of automobile storage batteries were shown and disclosed wide variation in voltage with temperature, degree of charge, and the condition of the battery. A vibrator frequency of one hundred cycles per second is most suitable for the self-rectifying type

of vibrator. Photomicrograms of tungsten contact surfaces magnified one hundred and fifty diameters showed granular structure of thirty thousand grains per square millimeter. Interlocked grains in a cross section of tungsten rod had fifty thousand grains per square millimeter. Other slides showed the heterogeneous structure of the material. Tungsten has proved to be the most satisfactory material for contacts probably because of the formation of suitable oxide. The gray oxide appears to prevent sticking while the higher blue oxide apparently causes it. Rebound is prevented by employing a rugged frame and proper reed dimensions and stress. The design of the transformer and electrical system is very important.

R. H. Sullivan, associated with Mr. Wallis, then presented a brief theoretical treatment of vibrators. The paper was discussed by Messrs. Crom, Hector, Huntsinger, Waud and others.

The January meeting of the Section was held on the sixth at the University of Buffalo. Chairman Crom presided and there were forty-one present.

George Lewis of the International Telephone and Telegraph Company presented a paper on "Radio Manufacturing in Europe." He outlined the relations of the various national and international communications companies with respect to operating and manufacturing. Slides illustrated views of research laboratories and factories. The existence of national economic restrictions which may result in discouraging uniformity in radio manufacture because of local political considerations were described. Illustrations were shown of several types of European broadcast receivers.

Chicago Section

On December 18, the annual meeting of the Chicago Section was held at the Hotel LaSalle and was attended by 100. H. C. Vance, chairman, presided. There were twenty-two at the informal dinner which preceded the meeting.

A paper on "A Stable Negative Resistance Oscillator of Small Harmonic Content" was presented by H. J. Reich, association professor of electrical engineering at the University of Illinois. In it Dr. Reich pointed out that a negative resistance oscillator, of which the dynatron is the most common example, has excellent frequency stability and low harmonic content when operated near the threshold of oscillation. Investigation of the Roberts' circuit which employs resistance neutralization, shows that its slope is such that the amplitude of the oscillator may be kept as small as desired. Experimental measurements indicate

that such an oscillator could be adjusted to give a total harmonic content of less than one-half per cent and high frequency stability, and is free from the objectionable features of oscillators which depend on secondary emission. Small oscillation amplitude is insured by use of automatic amplitude control which helps to maintain constant output over the frequency range.

In the election of officers, J. K. Johnson of the Wells-Gardner Company was designated chairman; J. E. Brown of the Zenith Radio Corporation, vice chairman; and V. J. Andrew, consulting engineer, was named secretary-treasurer.

Cincinnati Section

The November meeting of the Cincinnati Section was held on the 24th and attended by thirty-six. G. F. Platts, vice chairman, presided and the meeting was held at the University of Cincinnati.

Austin Armer of the Engineering Sales Department of the Magnavox Company presented a paper on "Photo-Radio Analogs." These comprised a number of rigid analogies between radio and photography. One was the similarity between the emulsion exposure curve of a film and the plate-current—grid-voltage curve of a vacuum tube. Both curves exhibit cutoff and saturation regions. The use of emulsions giving different gamma ratios was compared to using tubes with different amplification factors. Several excellent photographic slides were exhibited and demonstrated the effects of underexposure and overexposure. Principles of color photography were outlined and slides of several commercial types shown. The paper was discussed by Messrs. Farnon, Freeman, and Osterbrock.

C. D. Barbulesco, chairman, presided at the annual meeting of the section which was held at the University of Cincinnati on December 15 and attended by forty-six.

A paper on "Stabilized Feedback" was presented by C. E. Kilgour, research engineer for the Crosley Radio Corporation. The speaker reviewed the derivation of equations for feed-back conditions as given in Black's original paper. Charts showing decibel loss and output phase angle as functions of the B product and the loop phase angle were shown. With their aid, the performance of simple circuits was formulated, and demonstrated phase angle correction, frequency distortion correction, hum reduction, harmonic distortion reduction, and the conditions for stability of gain of an amplifier. Recent circuits utilizing degeneration in the output tube circuit only were shown and how each circuit affected the effective plate resistance of the tube was explained.

In the election of officers, G. F. Platts, engineer-in-charge of Stations WLW, WSAI, and W8XAL was designated chairman; W. W. Boes of the W. W. Boes Company, vice chairman; and A. P. Richards of the Crosley Radio Corporation was named secretary-treasurer.

Cleveland Section

The December 18 meeting of the Cleveland Section held at Case School of Applied Science was attended by forty-six. R. M. Pierce, chairman, presided. As this was the annual meeting, new officers were elected. R. A. Fox of the United Broadcasting Company was named chairman; W. F. Akers of Strong-Carlisle-Hammond Company, vice chairman; and R. L. Kline of Kladag Radio Laboratories was designated secretary-treasurer.

H. S. Knowles, chief engineer of the Jensen Manufacturing Company presented a paper on "Recent Acoustical Improvements in Radio Receiver Design." He outlined briefly the history of loud-speaker development and the use of electrical and mechanical analogies in an investigation of the subject. Several systems employed to improve low-frequency response were outlined. He described some recent developments of a cabinet having an opening in the back of approximately one square foot in area and the walls of which are acoustically treated to lower the natural period of resonance. Performance of speakers in such a housing was indicated by graphs.

Connecticut Valley Section

The annual meeting of the Connecticut Valley Section was held on December 17 in the Hartford Electric Light Company Auditorium. M. E. Bond, chairman, presided and there were fifty-three present.

In the business meeting, K. S. Van Dyke was designated to present to the Connecticut State legislature the endorsement of the section of recommendations on the "Minimum Needs of Connecticut State College."

In balloting for new officers, F. H. Scheer of the F. W. Sickles Company was elected chairman; D. E. Noble of Connecticut State College, vice chairman; and B. E. Atwood, United American Bosch Corporation, secretary-treasurer.

J. J. Lamb, Technical Editor of *QST* presented a paper on "Reducing Noise in Radio Communication." He pointed out that interference may be of an oscillatory or nonoscillatory type. The form of interference may be damped or undamped. Nonoscillatory interference may be of the separated pulse type as a spark or continuous pulse type as

generated by a commutator. Interference may be reduced before reaching the receiver by means of special antennas and the use of line filters. In the receiver, it may be reduced by using limiting devices in the audio-frequency circuits or in the radio-frequency circuit by high selectivity, noise silencing which momentarily disables the intermediate system, and superregenerative detectors. The use of selectivity and noise-silencing circuits was demonstrated using as a source of noise the spark from a high tension ignition coil and by a relaxation oscillator discharging through a spark plug.

Detroit Section

E. C. Denstaedt presided at the annual meeting of the Detroit Section which was held on December 18 in the Detroit News Conference room. There were fifty-two present and twelve attended the dinner which preceded the meeting.

A paper on "Recent Developments in Electronic Control" was presented by R. A. Powers, chief engineer of the Electronics Control Corporation. He described briefly several problems which had been solved through electronic control. These included a fabric tester which indicated loss of pile, color, and imperfection in weave as the cloth is rolled from one bolt to another. A brief description was given of an apparatus for sorting rock salt and automatically ejecting discolored lumps by a jet of compressed air controlled by a photoelectric cell and amplifier, the whole equipment being designed to work in the salt-laden atmosphere of a mine. There was also described camera equipment for taking high speed pictures of the finish of a horse race. A "smoothness gauge" to record the quality of a finished surface consists of a piezoelectric pickup which is drawn over the surface of the material. Its output is passed through an amplifier having uniform amplification up to 1000 cycles. Its output drives a piezoelectric recording pen which draws a magnified outline of the surface on a paper tape. The equipment enables a direct comparison between the smoothness of two surfaces and the establishment of standards for surface finishing. Its advantage over an optical lever type of recorder is that it may be used in the presence of vibrations from machinery and will hold its calibration for long periods of time. It was discussed by Messrs. Byerlay, Roush, and Shaffer.

In the election of officers, R. L. Davis, a consulting engineer, was designated chairman; E. H. Lee of the Federal Communications Commission office, vice chairman; and H. S. Gould of the University of Michigan was re-elected secretary-treasurer.

Emporium Section

The annual meeting of the Emporium Section was held on December 10 at the Sylvania Club with R. R. Hoffman, chairman, presiding. There were eighty-two present and all attended the dinner which preceded the meeting. M. I. Kahl of the Hygrade Sylvania Corporation was elected chairman; H. W. Abbott of the same company, vice chairman; and R. N. Palmer also of that company was designated secretary-treasurer.

An award set up in January for that member of the section, exclusive of the Executive Committee, who had done most to promote the activities of the section throughout the year was presented to Dr. Kievit who, in responding spoke briefly of actions of the Sections Committee at its meetings at Cleveland and Rochester. M. I. Kahl was presented with an Institute membership emblem in appreciation of his efforts as a member of the Executive Committee.

William Wilson, assistant director of research at Bell Telephone Laboratories presented a paper on "Research Organization." In it Dr. Wilson briefly outlined the historical evolution and development of the Bell Telephone Laboratories and pointed out the many scientific and engineering aspects of problems attending such a complex service as a telephone system. He discussed many ramifications encountered in the solution of generalized problems and demonstrated the need for a common meeting ground upon which a subdivision of problems of individualized telephone units might be made. To solve more expeditiously the problems common to these many individualized units and to promote co-ordination, standardization, and better and more salable service the Bell Telephone Laboratories were organized. A general problem breaks down into many problems of highly specialized character as it progresses from its embryonic stage of an idea to its finished product form of a service. Coursing its way through pure research, development, manufacture, distribution, and operation and maintenance in engineering fields, the product emerges as a materialized integration of compromises wrought by highly specialized demands upon it. That these compromises may represent the best over-all product achievable with the existing state of the art, the pathway along which a product passes must undergo examination by highly specialized minds for competent analysis.

Los Angeles Section

A meeting of the Los Angeles Section was held at the Los Angeles Junior College on November 17 with C. R. Daily, chairman, presiding. There were thirty-nine present at the meeting and eleven attended the informal dinner which preceded it.

A paper on the "Mt. Palomar Short-Wave Radiophone Link" was presented by S. S. MacKeown of the California Institute of Technology. The radiotelephone link which Dr. MacKeown described is used in connection with the construction of the two-hundred-inch telescope at Mt. Palomar and permits communication from there to the California Institute of Technology. The effects of atmospheric humidity on the refraction of the waves was considered in detail. A description of the equipment was given.

The December meeting of the section was held on the 15th at the studios of KNX. C. R. Daily, chairman, presided and there were ninety-five at the meeting. Twenty-two attended the informal dinner which preceded it.

The first paper on "Development of a High Fidelity Receiver" was by J. F. Blackburn, consulting physicist, who described the development of a high fidelity receiver and presented a demonstration of it in comparison with several other broadcast receivers.

The second paper was on "Monitoring Broadcast Transmission" by Harry Spears, audio-frequency engineer, of the Columbia Broadcasting System. The paper was based on the new equipment installed at KNX. It was pointed out that monitoring is purposely limited in quality so that the monitoring engineer can compensate for the effects of long land lines and other system limitations. The paper was concluded with a demonstration of lateral and vertical cut records. It was discussed by Messrs. Beeman and Hilliard.

As this was the annual meeting, new officers were elected. Douglas Kennedy of Los Angeles Junior College was elected chairman; R. O. Brooke of the National Broadcasting Company was named vice chairman; and F. G. Albin of United Artists was made secretary-treasurer.

New York Meeting

The annual meeting of the Institute was held in the Engineering Societies Building on January 6. Professor Hazeltine read a short note from the retiring vice president, Valdemar Poulsen, and after a brief résumé of Institute activities during 1936, introduced President Beverage. A short statement was presented by him. The technical portion of the meeting was devoted to the presentation of the five reviews on developments in radio in 1936 which will be found elsewhere in this issue. The meeting was attended by 350 members and guests.

Philadelphia Section

On December 3 a meeting of the Philadelphia Section was held in the Engineers Club. Irving Wolff, chairman, presided and there were 280

at the meeting. Twelve were present at the dinner which preceded it.

L. J. Hartley of the General Electric Company Bridgeport plant presented a paper on "Production Testing Equipment." He described the factory, its testing equipment, the arrangement of assembly belts and roller tables to facilitate testing, and the associated equipment. The use of a few crystal oscillators to control many frequencies, a master oscillator system for generating testing currents, low impedance cables for their distribution throughout the factory, and the centralization of power control apparatus immediately adjacent to the master frequency oscillator were described.

All equipment is panel-mounted which provides easy accessibility and rapid interchangeability. Twenty frequencies between 145 kilocycles and 60 megacycles are generated. Some are modulated at 400 or 500 cycles and others at 3500 and 10,000 cycles. In addition, an audio-frequency sweep signal is provided for testing loud-speakers. Distribution cables are insulated with low capacitance rubber for frequencies up to six megacycles and air-insulated for the remainder. Cables are lead-covered and carried in channel iron racks. Radio-frequency leakage is minimized by bonding cables and racks every eight feet. About one hundred and fifty final test positions are supplied from the distributing system. Test positions are equipped with panels for a loud-speaker, output and hum meter, line selector and attenuator, power supply and filter, and terminals for radio-frequency alignment. At the intermediate-frequency alignment positions are panels for a loud-speaker, an audio-frequency amplifier for the vertical deflecting plates, a cathode-ray oscilloscope, line coupling and attenuator, power supply and filter and terminals. The intermediate-frequency master oscillator is equipped with a motor-driven variable capacitor which gives a special wave form that can be easily observed on the cathode-ray oscilloscope. The paper was discussed by Messrs. Field, McIlwain, More and others.

Pittsburgh Section

B. Lazich, chairman, presided at the December 15 meeting of the Pittsburgh Section which was held at the Fort Pitt Hotel and attended by twelve.

A paper on a "Push-Pull Stabilized Triode Voltmeter" was presented by C. Williamson, professor at Carnegie Institute of Technology and John Nagy of the U. S. Bureau of Mines. In the circuit described, the circuit constants were fixed and the tubes were matched to them by changes in amplification factor and transconductance effected by adjustable shunt resistors. This adjustment is easy to make and once

the amplification factor balance is obtained, the supply voltage can be varied by five per cent with no loss of precision. Voltages of the order of 10^{-5} can be measured when the instrument is used with a suitable output circuit galvanometer. The instrument was exhibited and the paper was discussed by Messrs. Allen, Gabler, Krause, Miller, Stark, and Sutherlin.

Seattle Section

On December 4 a meeting of the Seattle Section was held at the Swedish Hospital and attended by fifty-three. E. D. Scott, chairman, presided.

J. E. Henderson, professor of physics at the University of Washington, presented a paper on "The Projection of 800-Kilovolt Electrons into Space." The objective of the research work which was described is to obtain the radiation emitted when a high velocity electron collides with an atom from various types of material. This requires a high energy beam of electrons and the paper dealt mostly with the construction and operation of an electron gun to produce this beam. The paper was closed with a demonstration which showed the effects produced on various materials when placed in the high energy beam. The equipment is contained in a thick walled concrete room and viewed through a window. After the demonstration, the equipment was turned off and the apparatus examined more closely.

Toronto Section

On December 14 a meeting of the Toronto Section was held at the University of Toronto and presided over by B. deF. Bayly, chairman. There were ninety present and ten of these attended the dinner which preceded the meeting.

D. G. Geiger, transmission engineer of the Bell Telephone Company of Canada, presented a paper on "Telephone Lines for Radio Program Transmission." The speaker analyzed first the composition of familiar tones. It was then pointed out that the range of the human ear extends from ten cycles to 25,000 cycles in frequency and from zero to 120 decibels in volume. Further tests have shown that if frequencies from fifty to eight thousand cycles are transmitted for radio programs, the quality is sufficiently good so that very few people notice any marked improvement if the range is extended.

The transmission engineer must maintain the same quality at all repeater stations along a telephone circuit and information was given on the methods and equipment to accomplish this. To overcome the effects of attenuation and phase distortion, repeaters are used every fifty miles and adjusted to compensate for the effects on the signal of

the section of line with which the repeater is associated. To correct for the effect of the line capacitance, loading inductances are located every three thousand feet. In addition, a bridge circuit automatically holds the resistance of the circuit to a desired fixed value in spite of the effects of temperature changes on the line. Cross sections of various telephone cables were shown and methods of spacing and arranging pairs to avoid cross talk explained. Signal levels are maintained as low as noise and cross talk will permit because of the modulation effect of the loading coils at higher levels. Open-wire lines were described and their lower attenuation per mile pointed out. Repeaters may be spaced one hundred and fifty miles apart. The moisture condition of the line is an important factor and variations require compensation.

The paper was closed with a demonstration of the effects of the various factors met with in transmitting programs over telephone circuits. Analysis of the tones produced by various musical instruments was given by records. The improvements in records during the past few years were demonstrated and it was evident that present-day records produce much less background and needle noise and have a greater frequency range as well as an increased range of volume level.

Washington Section

The annual meeting of the Washington Section was held on December 14 in the Potomac Electric Power Company auditorium. There were fifty-four present and twenty-nine attended the dinner which preceded the meeting. C. L. Davis, chairman, presided.

A symposium on government radio communication subjects was comprised of short papers presented by the following: T. A. M. Craven, chief engineer, Federal Communications Commission; J. H. Dellinger, chief of the Radio Section of the National Bureau of Standards; and H. G. Dorsey, principal electrical engineer of the U. S. Coast and Geodetic Survey. A sound motion picture on "Coast Guard Communications" was presented by the U. S. Coast Guard.

In the election of officers, W. Burgess of the Naval Research Laboratories was named chairman; G. C. Gross of the Federal Communications Commission, vice chairman; and E. H. Rietzke of the Capital Radio Engineering Institute was designated secretary-treasurer.

Correction

On page 1509, formula 10, of the paper "This Matter of Contact Potential," by R. M. Bowie, which appeared in the November, 1936, issue of the Proceedings, the quantity E_p/μ should be preceded by a minus sign.

Proceedings of the Institute of Radio Engineers
Volume 25, Number 2 *February, 1937*

TECHNICAL PAPERS

RADIO PROGRESS DURING 1936

Part I—Report by the Technical Committee on Electroacoustics*

Introduction

THE radio engineer is, in general, interested in three major divisions of applied acoustics; namely, instruments for the conversion of electrical into acoustical vibrations and vice versa, the transmission of sound through the air and its environs, and the sensations produced by the impact of the waves upon the ear drum. The great strides made in these fields in the past few years may in a large part be accredited to the remarkable developments in laboratory technique and equipment which have furnished the engineer with proper tools for carrying on intelligent experimental research and development. In addition, the use and extension of the existing theory have facilitated the solution of complete and extended investigations. Passing from the general to the specific applications of applied acoustics in radio, the subjects may be classified as loud-speakers, microphones, telephone receivers, studios, physiological acoustics, instruments, and technique for making acoustical measurements, theoretical studies, etc.

It is the purpose of this report to consider the progress and advancement that have been accomplished in the divisions outlined above during the past year. Of course, progress has been a gradual process during the past few years, and the advancement in certain divisions cannot be ascribed to a specific year. In this report, these intangible advances will be considered in the cases where a definite culmination has been achieved.

Loud-Speakers

The performance of loud-speakers used in radio receivers has been improved during the past year by advancements in the design of the speaker mechanism and by the development of suitable acoustic systems for coupling the driving system to the air. In the low-frequency range the following advancements have been made: Extension of the low-frequency limit of reproduction, improved efficiency, smoother response-frequency characteristics, and reduced nonlinear distortion. The high-frequency range has been improved by an extension of the

* Decimal classification. 621.385.97. Presented before New York Meeting, January 6, 1937.

range, a more uniform response-frequency characteristic, a broader and equalized spatial distribution, and an improved efficiency.

Among the first devices used commercially to mitigate or to remove cabinet resonance was an "absorption" system consisting of one or more Helmholtz resonators placed within the cabinet with the mouths of the resonators located in an effective position. Further study and use have been made of this system during the past year. The size and position of the resonators are the important factors which influence the performance of the over-all system. The net result of a properly designed resonator system is a more uniform response characteristic and an extension of the low-frequency range.

The acoustical labyrinth[1] consists of an absorbent walled conduit tightly coupled to the back of a cone loud-speaker diaphragm. Its open end discharges through an opening in the bottom of the cabinet within which it is folded. Further investigation of its performance made during the past year shows that the labyrinth obeys the theory of a piston-driven tube, modified by absorption at the walls. An antiresonance occurs when the tube is one-quarter wave length long. At this frequency the impedance becomes a very high resistance. The deleterious effect of the primary mechanical resonance of the loud-speaker may be eliminated by choosing the constants so that the frequency of the mechanical resonance of the loud-speaker occurs at the antiresonance frequency of the tube. This frequency is approximately an octave below the cutoff frequency of the system. At the first half-wave-length resonance, the impedance becomes essentially that of the open end and there is a phase reversal through the tube. The velocity at the open end is then in phase with that at the front of the diaphragm, the radiation from both sources is additive and an increase in response is secured. The rising absorption of the tube lining damps out the higher order resonances, the impedance remaining predominantly resistive and transmission being very small above about 150 cycles. Measurements indicate the complete elimination of the usual cavity resonance, a substantial extension downward of the frequency range and a large improvement in the fidelity of response to impulsive sounds.

The acoustic phase inverter or "Magic Voice,"[2] introduced commercially this year, consists of a loud-speaker driving mechanism mounted in a back-enclosed cabinet with a pipe or several pipes coupling the cabinet volume to the air. This system in its simplest form consists of the loud-speaker acoustic reactance and radiation resistance connected in series with the acoustic capacitance of the cabinet, the

[1] Benjamin Olney, *Jour. Acous. Soc. Amer.*, vol. 8, no. 2, p. 104, (1936).

[2] C. O. Caulton, E. T. Dickey, and S. V. Perry, *Radio Eng.*, p. 8, October, (1936).

cabinet capacitance being shunted by the acoustic reactance and radiation resistance of the tubes. The phase of the volume current on the front side of the cone differs from that on the back side by 180 degrees. The phase of the volume currents in the capacitance of the cabinet and inertance of the tubes may differ by 180 degrees in case of no resistance and in the case of resistance, somewhat less, depending upon the amount of resistance. Therefore, the constants may be chosen so that the volume currents issuing from the front of the cone and the tubes are practically in phase. This system increases the effective radiation resistance and reduces the effective reactance. The low-frequency range is increased and a smoother response characteristic is obtained.

The combination horn and direct radiator loud-speaker[3] consists of a horn coupled to the back side of a cone loud-speaker mechanism and an acoustic capacitance for changing the output from the horn to the open side of the cone for the reproduction of the mid- and high-frequency ranges. The combination of a horn and cone results in high efficiency and smooth response at the low frequencies. By suitable selection of constants in this system the cone can be made small for good efficiency and wide distribution as a direct radiator for the mid- and high-frequency ranges. A cone with a single coil is used for reproduction to 7000 cycles. For reproduction to 12,000 cycles a double voice coil is used in place of a single voice coil driving system. This loud-speaker has been introduced during the past year as a monitoring loud-speaker in broadcast stations, sound motion picture recording, and high quality radio reproduction.

The high-frequency range of the better radio receivers has also been extended during the past year. For this moderate increase in range, an aluminum voice coil driving a suitably processed cone has been employed quite extensively.

With the extension of the high-frequency range, there has been an increased use of deflectors and diffusers for spreading the high-frequency radiation, particularly in the case of large cones. These have, in general, been of two types: the large vane which acts as a reflector and the small multivane type which is coupled close to the cone and functions as a multihorn. Quite uniform directional characteristics may be obtained with properly designed diffusers or deflectors.

Considerable attention has been directed toward reduction of nonlinear distortion in loud-speakers used for the higher grade radio receivers. Studies and developments have been made of new suspensions which have a more nearly constant stiffness over large amplitudes.

[3] H. F. Olson and R. A. Hackley, Proc. I.R.E., vol. 24, pp. 1557–1566; December, (1936).

Large field structures, together with well-designed voice coils, have reduced distortion by maintaining a constant "flux-turns" product with amplitude.

New magnetic materials have made it possible to design small and economical permanent magnet field structures for dynamic loud-speakers, with air gap flux densities comparable to those obtained with electromagnets. Consequently, permanent magnet dynamic loud-speakers have found widespread use during the past year in battery-operated receivers, centralized radio, and other applications where electrical field excitation is not readily available or expedient.

Complete screening of the air gap has, in the past, been reserved for speakers used in surroundings carrying large amounts of dust and ferromagnetic particles. With reduced voice coil air gap clearances, to obtain greater over-all efficiency and a reduction of field excitation, screening has become almost imperative for all types of loud-speakers, regardless of their use.

The reduction of noise due to various kinds of interference in automobile receivers has made it possible to extend the high-frequency range. In order to maintain a balanced response characteristic a corresponding increase in the low-frequency response is necessary. In one type of dash loud-speaker introduced this year, the low-frequency range has been extended, by sealing the back edge of the case to the fire wall which has holes drilled for coupling the "case volume" to the outside air. Another arrangement that has been introduced to extend the frequency range consists of a large low-frequency loud-speaker, which may be located out of the way under the dash and a small high-frequency loud-speaker mounted in the dash or header for good distribution of high-frequency radiation.

Loud-Speakers in Allied Fields

In the allied fields of sound motion pictures, sound re-enforcing, public address, and general announcing high power and high efficiency loud-speakers are required. Some of the advancements made in these fields during the past year will be briefly described.

For sound motion picture reproduction in large theaters a two-channel loud-speaker[4,5,6] has been generally adopted. This system consists of a short horn, either straight or folded, driven by two or more dynamic loud-speakers for the reproduction of low frequencies. High frequencies are reproduced by specially designed dynamic units driving

[4] John Hilliard, Academy Research Council, March, (1936).
[5] John Hilliard, *Electronics*, p. 24, March, (1936).
[6] Flannagan, Wolf, and Jones, Society of Motion Picture Engineers, Rochester Convention, October, (1936).

a multicellular horn. Several of these horns are available with different numbers of cells and arrangements to permit the most satisfactory distribution of sound in theaters of different shapes. The output from the amplifier is distributed between the two elements by means of the dividing network. The overlap region is usually placed somewhere between 200 and 500 cycles, depending upon the design of the loud-speaker elements. Both the high- and low-frequency loud-speakers are installed in one compact assembly which may be either flown or mounted on the stage.

The compound horn loud-speaker[7] consisting of a single mechanism coupled to two horns, a straight axis high-frequency horn, and a folded low-frequency horn, has been used for reproduction in small theaters and for portable sound re-enforcing systems.

The re-enforcement and reproduction of sound in auditory perspective was extended to the open air theater during the past year. On the night of August 17 at the Hollywood Bowl a concert for the benefit of the Los Angeles Orchestra was presented. For this occasion a three-channel outdoor stereophonic sound re-enforcing system was set up. The level varied less than ± 5 decibels over the seating area for 22,500 people for a frequency range of 50 to 10,000 cycles, and a re-enforcement of about 16 decibels was realized.

Head Telephone Receivers

The continued use of head telephone receivers is due to the many advantages possessed by this type of sound generator for monitoring in radio broadcasting and for certain applications in radio reception, particularly in limited spaces and temporary locations.

A dynamic type of telephone receiver[8] having uniform response over a wide frequency range has been developed and introduced. A new type of vibrating system compensates for the loss of low-frequency response due to the normal leak between the ear cap and the ear. Uniform response is maintained at the high frequencies by employing a system of small effective acoustic mass reactance.

Microphones

The general fidelity, involving such considerations as frequency range, uniformity of response, and distortion, of high quality microphones has always been superior to that of loud-speakers. It is a comparatively simple matter to design a microphone with uniform re-

[7] H. F. Olson and F. Massa, *Jour. Acous. Soc. Amer.*, vol. 8, no. 2, p. 48, (1936).

[8] H. F. Olson, *Jour. Soc. Mot. Pict. Eng.*, vol. 27, no. 5, p. 539, (1936).

sponse over a wide frequency range. However, a universal microphone with one set of fixed characteristics does not adequately satisfy the manifold problems of sound collection. For example, both directional and nondirectional microphones have definite applications; nonuniform response over a limited range may be fitted for pickup and transmission under certain conditions; weight and size may sometimes be a consideration; while for other uses, high output may be more desirable than small weight, etc. Consequently, during the past few years microphones have been developed to satisfy some new problems in sound pickup or to effect an improvement over existing microphones used in some collection problem.

For wide angle distortionless pickup, a moving coil microphone[9] which responds uniformly to sound arriving from any direction was developed. The appearance of the microphone is the direct outcome of research studies of diffraction, the principal cause of directivity in other pressure type microphones. The small spherical shape reduces diffraction to a minimum while the flat circular screen in front of the diaphragm practically eliminates the remaining directivity. A novel design of the diaphragm and magnet structure achieves a smooth response characteristic together with an unusually high ratio of output level to weight. If studio technique or undesirable acoustic interference requires the use of a semidirectional microphone like the existing conventional dynamic type a diffraction baffle is available. This consists simply of an annular disk which fastens over the front of the microphone in place of the acoustic screen. Consequently, the new microphone has a wider field of application than former types and its small size and greater ruggedness render it still more attractive.

Directivity has been found to be desirable in certain sound collecting systems to improve the ratio of direct to generally reflected sounds and otherwise to discriminate against undesirable sounds. The bidirectional ribbon microphone is a pressure gradient instrument, in which the response corresponds to the velocity component in a sound wave. The pressure ribbon microphone is resistance controlled, and the response is a measure of the pressure component in a sound wave. A combination of the outputs of the pressure and velocity ribbon microphones produces a unidirectional characteristic. This unidirectional microphone[10,11] has been found to be useful in sound motion picture recording, radio broadcasting, and sound re-enforcing systems

[9] R. N. Marshall and F. F. Romanow, *Bell Sys. Tech. Jour.*, vol. 15, no. 3, p. 405.

[10] Weinberger, Olson and Massa, *Jour. Acous. Soc. Amer.*, vol. 5, no. 2, p. 139, (1933).

[11] H. F. Olson, *Jour. Soc. Mot. Pict. Eng.*, vol. 27, no. 3, p. 284, (1936).

in which the desired sounds originate in front and the undesired sounds to the rear of the microphone.

Several new types of microphones employing Rochelle salt crystals have been developed as follows: a spherical nondirectional general purpose crystal microphone operating directly into a vacuum tube; a single diaphragm type crystal microphone with a high capacitance crystal element, which permits using long cables without serious loss of output; semidirectional microphones, both of the direct and diaphragm actuated crystal type:

A velocity or pressure gradient condenser microphone[12] has been developed. The action depends upon the variation in capacitance between the vibrating ribbon and an insulated metallic grill.

Electromechanical Instruments

There have been numerous advancements in the field of sound recording and reproduction by means of disk recordings.

During the past year the improvements on the volume expander have been in the nature of reduction of distortion.

A new pickup[13] has been developed for phonograph reproduction. the lighter vibrating system has extended the range to 8000 cycles. The pickup pressure on the record has been reduced from $3\frac{1}{2}$ to $1\frac{1}{2}$ ounces, which reduces the surface noise and decreases record wear. High sensitivity has been maintained.

A new vertical disk pickup or reproducer has been developed in which the vibrating system is substantially lighter than previous reproducers. The system is practically aperiodic and operates at a stylus pressure of less than an ounce. Its response is uniform over a frequency range of 11,000 cycles at about the same efficiency as other reproducers of the moving coil type. The stylus is of diamond and requires no replacing.

With the rapid increase in the use of both lateral and vertical disk records in broadcasting, the desirability of a pickup responsive to both types of records became apparent. This need is fulfilled by a moving coil device, so constructed that either lateral or vertical displacement of a permanent (diamond) stylus produces a vertical displacement of the coil, the ratio of the velocities of the coil and of the stylus being substantially constant over a wide range in frequency (about 8500 cycles for both types of reproduction). The operating stylus pressure is $1\frac{3}{4}$ ounces.

[12] *Electronics*, p. 21, September, (1936).
[13] C. M. Sinnett, Institute of Radio Engineers, Cleveland Convention, May, (1936).

A new type of driving and filter system for record turntables has been developed and introduced which has a very small speed variation at both $33\frac{1}{3}$ and 78 revolutions per minute.

There have been a number of developments made in direct recording and reproducing apparatus[14] and record materials so that this type of reproduction is now suitable for many uses.

Studio Acoustics

The design of studios for sound collection has been advanced to the point where it is possible to state definitely the conditions that are required for a studio to be satisfactory under a wide variety of conditions. Of course, all these improvements have been gradual over a ten-year period and cannot be ascribed to the past year. Instruments such as new microphones are discrete and distinct and may be relegated to a particular year. On the other hand, broadcast studio design has been evolved by a series of steps during the past ten years. However, during the past year publications[15,16] have shown that the design of studios is now a fairly definite and precise engineering job. It is the purpose of this section to summarize briefly some of the salient factors of these publications.

The studios should be graduated in size and in corresponding acoustical condition to accommodate anticipated loading to the best advantage. Broadcast operating technique requires the provision of space for the control booths so located that the studio engineer has an unobstructed view of the studio.

The problem of sound insulation is a very important one because, obviously, simultaneous operation of all the studios must be possible without mutual interference or disturbance from extraneous noises. The construction and selection of materials for obtaining good sound isolation can now be specified. Cinder composition has been found to be more desirable than terra cotta. Reduction of "mechanical noises" is accomplished by the resilient mounting of the studio walls, floor, and ceiling.

Noises which may be carried into the studios by the air conditioning or ventilating ducts may be suppressed by lining the ducts with felt, rock wool, etc., to obtain suitable attenuation of the sound carried by the air in the duct, and by isolation of the duct at regular intervals to suppress vibrations carried by the material of the duct. The prevention

[14] A. C. Kellar, Acoustical Society of America, New York Meeting, October, (1936).

[15] R. M. Morris and G. M. Nixon, *Jour. Acous. Soc. Amer.*, vol. 8, no. 2, p. 81, (1936).

[16] R. M. Morris and G. M. Nixon, *RCA Review*, vol. 1, no. 2, p. 64, (1936).

of "breathing" by sealing the walls against air flow before application of the acoustic treatment has reduced the quantity of dust collected by the acoustic material.

One of the important factors which determines the performance of a studio is the reverberation time. The relationship between reverberation time and volume has been determined primarily from experience. The acoustic material is the important factor in obtaining the correct reverberation time. Methods of measuring test samples have been established which eliminate the discrepancy usually found between the actual absorption found in studios and the absorption attributed to the material. The optimum reverberation time characteristic may be obtained in a studio by a sufficient area of one treatment having the desired frequency absorption curve. The use of the proper relative areas of two or more treatments of complementary characteristics to secure the proper total absorption is usually preferable because of the latitude afforded in the decorative treatment of the studio. The achievement of good artistic effects, together with good acoustics, may be accomplished by suitable choice and placement of the material.

In all cases parallel and opposite reflectant surfaces should be avoided to prevent persistent reflections or flutter. Where it is necessary to place large reflectant areas in opposition, the surfaces should be distorted or ornamentally treated to disperse effectively impinging sound.

Measuring Instruments

The most significant characteristic which depicts the performance of a loud-speaker is the response or sound pressure vs. frequency characteristic. During the past year considerable work has been carried out on the development of various types of equipment for obtaining response characteristics.

Several different types of logarithmic voltmeters, which make it possible to record directly in decibels, have been developed. Further developments have been carried out, employing the remote cutoff vacuum tube for logarithmic voltmeters. Use has also been made of the logarithmic relation between the grid current and voltage to obtain a logarithmic voltmeter having a range of 50 decibels in a single tube.

The development of automatic curve drawing equipment has received considerable attention during the past year. One of these instruments employs a motor to drive both the pen stylus which traces the curve and the attenuator in such a manner that the output of the amplifier always matches a fixed voltage. In another form of this method a variable voltage determined by the settings of a potentiometer is balanced against the output of the amplifier. In some systems

the attenuator or potentiometer is driven in a forward and backward direction by a double-clutch arrangement. In another system the attenuator driving motor is driven by thyratrons which are controlled by the unbalanced voltage—unbalance in one direction causes rotation in one direction; unbalance in the opposite direction will reverse the motor. These systems are suitable for obtaining response-frequency characteristics of amplifiers, reverberation characteristics of rooms, etc.

A vibration pickup[17] has been introduced by means of which certain mechanical motions or vibrations may be converted into the corresponding electrical currents. The output is sufficiently high to permit direct connection to the input circuits of a cathode-ray oscillograph.

A direct indicating frequency meter[18] with a range 0 to 5000 cycles has been developed and introduced. The meter consists essentially of an amplifier, a gas discharge tube, counter circuit, diode switching tube, frequency indicator meter, and power supply.

A pointer frequency meter[19] based on the measurement of the ratio of the currents in parallel circuits with resistance and reactive impedances by means of a direct-current log ohmmeter and a copper-oxide rectifier has been described. The frequency meter is applicable over a frequency range as high as 20 kilocycles. Power requirements are small, being of the order of one watt.

A hum meter has been designed and built for use in radio receiver development. It has a low impedance input (about 0.3 ohm) and is connected directly in series with the voice coil circuit to be measured. The hum voltage generated across this low impedance is amplified by a two-stage amplifier and after passing through a compensation network is read on an audio-frequency microammeter. The compensation network corrects for the acoustical characteristics of the ear and for the average radio loud-speaker, so that readings of the meter represent true loudness levels of hum. Since the meter measures hum current, it is free of the uncertainties connected with voltage measurements of hum in the voice coil circuit where several elements may be generating hum independently.

An electrical frequency analyzer[20] has been designed and built which operates through a large number of electric filters arranged in parallel, the frequencies in the different filters being distributed over the frequency range to be analyzed according to a logarithmic law. The amplitudes of the frequencies transmitted by the various filters are

[17] H. J. Schrader, Institute of Radio Engineers, Cleveland Convention, May, (1936).

[18] F. V. Hunt, *Rev. Sci. Instr.*, vol. 6, no. 2, (1935).

[19] K. Karandejew, *Tech. Phys.*, U.S.S.R., vol. 3, p. 361, (1936).

[20] E. Freystedt, *Zeit. für Tech. Phys.*, vol. 16, no. 12.

rendered visible by applying the corresponding potentials to a cathode-ray tube, so that an amplitude spectrum is obtained. With the frequency range from about 40 to 5000 and three filters per octave, the time for a complete analysis is only about 0.1 second, so that the spectrum can be regarded as practically simultaneous with the electric or acoustic phenomena in question. In the case of rapidly varying sound spectra a small film camera making about ten exposures per second has been found useful. Examples are given of the analysis of sounds and noises of various kind. This instrument has been used to investigate sounds of various types, including vowels and consonants and various wind instruments.

A motional impedance bridge has been developed consisting of a high gain detector in the null arm of a Heaviside bridge. If the speaker has an efficiency of 4 per cent it is necessary that the bridge have an accuracy of 0.2 per cent in order to make measurements with an accuracy of 5 per cent. It is difficult to attain this accuracy because of the small null arm voltage, harmonics in the oscillator, harmonics generated by the loud-speaker and because of voltages generated by the loud-speaker acting as a microphone. A suitable detector for the null arm consisted of an oscilloscope preceded by a high gain amplifier with a sharp filter. By means of the oscilloscope it is possible to differentiate the desired signal from various kinds of interference.

A meter[21] has been developed for measuring the speed variations of recording and reproducing machines. For testing turntables a toothed steel wheel was built in which special precautions were taken to minimize indexing and other possible errors. The current generated by means of this wheel is supplied to an electric circuit so arranged that variation in frequency causes deflections of a galvanometer, which are registered on a photographic film. The principle employed, namely, a resonant circuit off tune, has been used in earlier devices. In this meter a push-pull arrangement is used to reduce the errors due to variation in voltage.

A new purely acoustical process[22] for measuring acoustic impedance has been evolved. It is a null method in which the unknown impedance is compared with a calibrated arbitrarily variable impedance. Calibration of the equipment was extended over the range 427 to 1536 cycles by an electroacoustic method using standing waves.

Several new sound level meters have been developed during the past year. These instruments, save for certain refinements, are similar

[21] E. W. Kellogg and A. Morgan, *Jour. Acous. Soc. Amer.*, vol. 7, no. 4, p. 27, (1936).

[22] K. Schuster, *E.N.T.*, vol. 13, p. 164, (1936).

to those developed during the past few years. Tentative standards[23] have been established for noise meters which should be an aid in bringing about an agreement between various observers. Tentative standards[24] have also been established for noise measurements.

A room[25] intended for acoustical measurements under essentially free field conditions has been described. The absorbing material, which consists of a number of layers of cloth separated by air spaces is shown to have an absorption coefficient of the order of 98 to 99 per cent over a wide frequency range. Some data are also given showing the degree of departures of the sound field in the room from the field to be expected in free space. It is shown that it may not be possible to duplicate a free field in an enclosed room regardless of the freedom from interference obtained, because the pressure may decrease more rapidly than the inverse distance law applying to a free field.

A report on the calibration of microphones[26] has been prepared by a Subcommittee on Fundamental Sound Measurements of American Standards Association.

A report on Loud-Speaker Testing has been prepared by the Electroacoustic Committee of the Institute of Radio Engineers.

Acknowledgment

In conclusion, the committee expresses its appreciation for the cooperation of all those who have contributed to this project by direct communications or through published articles dealing with the subject of Electroacoustics.

[23] American Tentative Standards for Sound Level Meters.
[24] American Tentative Standards for Noise Measurements, *Jour. Acous. Soc. Amer.*, vol. 8, no. 2, p. 143.
[25] E. H. Bedell, *Jour. Acous. Soc. Amer.*, vol. 8, no. 2, p. 118, (1936).
[26] "Calibration of microphones," *Jour. Acous. Soc. Amer.*, vol. 7, no. 4, p. 300, (1936).

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RADIO PROGRESS DURING 1936

Part II—Report by the Technical Committee on Electronics*

THE year 1936 is more noteworthy in the field of electronics for continuation of the trends of recent years than for radical new developments. In general terms these trends are, on the one hand, increased knowledge, and application of this knowledge, of the behavior of free electrons in motion as functions both of time and of distance, and on the other hand, the utilization of mechanical structures requiring unusual precision or radically different methods of fabrication. As is to be expected, the technical literature indicates the greatest activity in the fields of ultra-short waves and television. Indeed, a worker in the field of electronics may take what satisfaction he can from the fact that progress is limited almost entirely by the accomplishments of his co-workers in these important new fields, inasmuch as their ultimate successful development now appears to depend upon the solution of certain clear-cut electronic problems. It is from the real progress that has been made along this line in the past year that the greatest encouragement may be drawn.

The workers in other branches of electronics have by no means been idle, nor have their efforts been unrewarded. In these branches, particularly those well past the pioneering period, fundamental developments are naturally relatively infrequent. This is in contrast to the situation some years ago when nearly every important advance in the field of radio depended to a greater or lesser extent upon improvements of thermionic devices.

Television Tubes

Although television is in the formative stage, activity at present is concentrated—though not exclusively—upon a narrow range of all-electronic methods of pickup and reproduction. The recent noteworthy steps that have been taken in the United States and abroad leading to the regular broadcasting of high fidelity television show most conclusively that there has been great progress in the practical development of the electronic devices upon which the several systems are based. Furthermore, it is well known that the research and development activity on television tubes has increased markedly. It is, therefore, somewhat surprising, at first thought, to find a relatively small number of papers published during the year which describe important practical advances. Of the various explanations which might be offered for this

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situation, perhaps the most agreeable is that the workers have been too busy to write.

Improvements through the use of better luminescent materials have been reported in the cathode-ray tube method of film scanning.[1,2] In this method the motion picture film is scanned by the image of a luminescent spot on a cathode-ray tube. The maximum amount of light from a small spot is required. While there undoubtedly has been much work on devices for direct pickup of outdoor and studio scenes (as contrasted with pickup from motion picture film), little in the way of important progress has been reported.

In the field of reproduction devices, there have been a number of contributions. A cathode-ray tube has been developed which when operated at 20,000 volts produces a sufficiently intense image on a small screen to permit the optical projection of this image on to a separate screen.[3] Zinc sulphide and mixtures of zinc sulphide with calcium sulphide have been used to produce approximately white luminescence with relatively high efficiency.[4]

In most new arts the theoretical lags behind the practical. As the art advances and matures, the analysts examine, explain, and improve the devices which have been developed and used. The cathode-ray television reproduction tube has entered this latter stage. The electron beam in such a tube is focused by an electron lens. While these lenses have been known and used for years, this year has brought forth a considerable number of contributions to the knowledge of their design and their properties.[5,6]

Of probable importance in the field of television is the work on electronic image transformers which permit the translation of images formed by infrared or ultraviolet light into visible images by electronic means,[7,8,9,10] and, in the process, produce by means of an electron lens a high quality electronic image of the optical image focused on the photocathode.

Ultra-High-Frequency Vacuum Tubes

Although ultra-high-frequency vacuum tubes are by no means new in the art of radio, the last few years have seen greater progress in bringing them out of the laboratory and into the field of useful application than the score of years preceding. The recent trend is toward those tubes in which the electron transit time is a small fraction of the high-frequency period, which is in contrast with the work of several years ago when emphasis was on the study of the effects of transit times critically valued in comparison with the oscillatory period. Progress during

[1] Numbers refer to bibliography.

the past year in tubes of the conventional type with negative control grid and in magnetrons with short transit times may be cited. The literature of the subject indicates that the trend has resulted from increased activity on short transit-time tubes rather than from neglect of the critical type, where a more complicated mode of operation naturally requires a longer development before the final possiblities can be realized.

In the field of tubes with negative control grid, oscillators have been developed and made available which give a useful output of 6.5 watts at 500 megacycles.[11] These tubes have very small dimensions, but the special feature about them is the glass technique employed to allow the leads and supports to be made suitable for ultra-high-frequency work. Amplifier tubes have been built to give an output in the neighborhood of ten watts at 150 megacycles with class B operation, or gains of twenty decibels with class A operation at the same frequency.[12] These tubes are pentodes operating in push-pull with two sets of tube elements in the same envelope, which also contains shielding between the input and output sides. The grids are mounted on cooling fins so that their location close to the filament does not produce overheating.

A number of theoretical and experimental studies have been of assistance in furthering this work. Some of these deal with the absorption of power from the input circuit of a high-frequency amplifier by electrons during their transit to the plate.[13,14,15] The loss may be expressed in terms of an equivalent shunting resistance between grid and cathode. In the case of a conventional receiving tube not especially designed for ultra-high frequencies, this resistance was as low as 5000 ohms at sixty megacycles, while in special tubes with very close electrode spacing it was 140,000 ohms at the same frequency. Another theoretical step has been the derivation of simple equivalent networks to represent the tube even at ultra-high frequencies.[16] In these networks the effect of transit time is included as a modification of the conventional network in general use at low frequencies.

In the development of magnetrons with short transit times, an outstanding advance has been the attainment of power outputs of the order of 100 watts at 600 megacycles.[17,18] This was accomplished by the inclusion of the tuned circuit within the tube envelope and by the use of circuit elements which afford high thermal conduction from the anodes, thus providing a large radiating surface and permitting effective water cooling.

Besides these developments in tubes with short transit time, a large number of investigations have dealt with magnetrons where the electron transit times are critically related to the oscillation

period.[19,20,21,22,23,24,25,26] The use of positive end plates to remove from the high-frequency field those electrons which have given up their contributions to the output has been described.[20]

In the case of the Barkhausen-Kurz type of tube, which also depends upon a critical transit time for its operation, an improvement in stability has been reported.[27] This was obtained by the use of a plate composed of three sections.

A type of tube which depends upon secondary emission for its electron supply has been described.[28] This represents an interesting departure from the conventional practice of using thermionic cathodes.

An important adjunct to the generation and amplification of ultra-high-frequency oscillations is the means of measuring them.[28,29,30,31,32] Vacuum tube voltmeters have been produced in which the tube consists of a minute diode.[29] The short length of the leads and reduced electron transit time permit these tubes to be used for voltage measurements at 300 megacycles with an error less than six per cent. Computed correction factors by which the error can be reduced to one per cent have been verified.

Receiving Tubes

In the field of small high vacuum tubes there has been a notable trend toward the use of electron-focusing or beam-forming phenomena. Advances have been made in the study of the underlying principles and in their practical application in the design of tubes with improved or new characteristics.[33,34,35,36,37] Among practical applications of beam effects have been amplifier and detector tubes in which the current to an electrode is varied by deflection of the beam[38] and amplifier tubes in which the current density in the beam is varied.[39]

Further advance has been made in improving the efficiency of power output tubes. Among the means used to accomplish this are: adoption of critical plate spacing which reduces the number of secondary electrons escaping from the plate by reason of the effects of space charge in the region near the plate; extension of the use of aligned grid laterals to reduce the current taken by the accelerating grid; the arrangement of grid laterals and supports and deflectors to reduce turbulence in the flow of electrons and to constrain them to move in parallel beams or sheets from the cathode to the plate.[40,41,42,43,44]

Increasing attention has been given to the design of receiving tubes for use at the higher frequencies. An example of this is the "remote cutoff" pentode of very small dimensions which has recently been made available.

Noise originating in vacuum tubes has become a problem of ever-

increasing importance because of the necessity for amplifying signals of the lowest practicable level. Much valuable work in this field has been reported during the past year.[45,46,47,48,49]

Transmitting Tubes

Outside of the field of ultra-high frequencies there has been little published on transmitting tubes. The most notable trend has been toward the elimination of direct-current generators for filament excitation by the use of filaments designed for polyphase operation and of indirectly heated cathodes suitable for alternating-current operation.

Gas Tubes

Gas tubes have become of great importance in nonradio fields and as a result have undergone such development that a worker in the field of radio tubes may well regard himself as an innocent, perhaps even ignorant, bystander. Nevertheless, these tubes are also of importance in radio transmitters, and therefore may properly be reported here.

The principal advances in the gas-tube rectified field have been in the direction of applying methods of control. Both hot-cathode mercury-vapor rectifiers and igniter-type tubes have been used for the purpose. The circuits have included not only voltage control but automatic breaker action in the case of overloads or arc-backs.[50,51,52,53]

Igniter-type tubes have been used in rectifiers supplying plate voltage as high as sixteen kilovolts for broadcast transmitters.[54]

A technique for lengthening the life of hot-cathode rectifier tubes through the adjustment of the relative phases of the cathode and anode voltages has been reported.[55]

A gas-filled amplifier tube has been described and made available which has a low plate resistance and high transconductance.[56] The working structure of this tube consists of conventional elements but with interelectrode spacings reduced so as to be small compared with the mean free path of the electrons in the mercury-vapor atmosphere.

Photoelectric Devices

Progress in the field of photoelectric devices has been confined chiefly to the so-called electron telescope or image tube in which, by optical and electron-optical means, infrared and ultraviolet light may be made to produce a visible image on a luminescent screen.[7,8,9,10]

Miscellaneous Electronic Devices

Further work has been reported on the electron multiplier, of both the constant-potential and the high-frequency types.[57,58,59,60] These

devices offer the possibility of the amplification of small photoelectric currents with reduced disturbances caused by random fluctuations.

A small high vacuum cathode-ray oscillograph tube enclosed in a conducting envelope and suitable for operation at the relatively low voltage of 250 volts has been described and made available.[61]

It is impossible to report adequately on the studies of thermionic, photoelectric, and secondary emission which are being made in numerous laboratories devoted to the study of pure physics. As in the past, these studies will continue to be of great importance to workers in the field of electronics.

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RADIO PROGRESS DURING 1936

Part III—Report by the Technical Committee on Radio Receivers*

Summary—*The Radio Receivers Committee presents a brief review of the status and progress of engineering work on radio receivers during the past year of 1936. This review deals mainly with broadcast receivers.*

The broadcast receiver industry has shown healthy growth during the year. The unit sales have increased from 6,000,000 to 9,000,000 and the dollar sales from $300,000,000 to $500,000,000.

The introduction of automatic frequency control in this country by several companies is an outstanding development of 1936 in the practical application of radio engineering. This improvement makes practical the "telephone-dial" selection of a few stations, which has recently been featured.

Progress is noted also in the following features: manual control of selectivity for greater fidelity or selectivity, at the option of the listener; octal-base glass tubes; ballast tubes; beam amplifier tubes for greater power output; stabilizing feedback to reduce distortion; beam indicator tubes and color indicators for visual tuning; frequency bands above and below the "all-wave" range; fixed and adjustable iron-dust cores in sharply tuned circuits; elevated antennas for motorcars; doublet antenna systems for noise reduction; noise impulse limiters; volume range expansion or compression; loud-speakers radiating more efficiently at low frequencies. Automatic control of selectivity by the use of stabilizing feedback has been the subject of major improvements not yet found in commercial receivers.

Developments are noted in the field of television receivers, amateur receivers, other special communication receivers, and signal generators.

Introduction

The Radio Receivers Committee of the Institute has been assigned the obligation of reviewing the status and progress of engineering work on radio receivers, during the past year of 1936. This is a continuation of the annual reviews for the years 1934 and 1935 which were ably prepared by R. H. Langley and published in the Proceedings.[1,2] These covered only broadcast reception as distinguished from other classes of reception, because the other reviews of those years covered such other classes as used in the mobile and point-to-point services. The present reviewing of 1936, however, is apportioned among the standing committees of the Institute, so that their lines of division define the scope of each review. From the standpoint of radio receivers, we look at the names of the other committees to determine their influence on the scope of this review. Antennas, vacuum tubes, and loud-speakers are here included only to the extent of their influence on the radio receivers as a whole.

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[1] Numbers refer to bibliography.

The preponderance of the radio receiver industry is the manufacture of broadcast receivers, which therefore receive much more attention than receivers in other classes. Also the mobile and point-to-point receivers comprising the other classes are less susceptible to generalization as to their characteristics and trends of design, because they are more highly specialized.

In this review, an attempt is made to summarize the status and progress of the radio receiver industry in 1936 from the commercial point of view, as well as from the standpoint of the engineer who is equally interested in the basic technical advancement. The year has abounded in both commercial growth and technical improvements. The radio engineers of this industry have contributed so much to its success that only a relatively small number of their contributions can be described in this summary.

The radio receiver industry is comparable with the automotive industry: Unfortunately, however, the public, the business executives and the salesmen can understand and appreciate mechanical improvements better than electrical. The riding ability of a motorcar is analogous to the freedom of transients in a loud-speaker, but the buyer who is supercritical of his shock absorbers pays little or no attention to how his loud-speaker behaves toward impulses of sound. The unit cost of radio sets is much lower because, while an auto has to carry a heavy load, a radio merely has to agitate the thin air in front of the loud-speaker. Therefore the weight and cost of a radio set can be reduced almost without limit, allowing a reasonable deficiency of the lowest tones, whose reproduction requires moving the greatest mass of air.

The great improvement of the performance of radio receivers has been made possible by the reduction of weight and cost of most of the components, so that more and better components can be employed in a single receiver. This progress is the life work of a thousand trained and experienced radio engineers, most of whom are employed by a hundred companies engaged in the manufacture of radio receivers. This review is intended to be a milestone in their progress and a monument to those of their accomplishments which were manifested in 1936.

The past year marks one decade of the operation of home radio receivers by socket power in place of batteries. This was the first year that a radio receiver which was more than a toy could be purchased complete at a list price under ten dollars, all ready to plug into the electric outlet. This receiver is not nearly as good as the average of present-day receivers, but it would have been a miracle of engineering to have built just one such receiver at any cost ten years ago. This type of receiver weighs under ten pounds and still gives better

performance, in many respects, than the hundred-pound receiver which sold ten years ago for a total price of hundreds of dollars. It is a superheterodyne which has only two knobs to operate, one for tuning and one for volume control. The carrier amplification is controlled automatically by the diode linear detector. The five tubes do the work of seven. The illuminated dial is calibrated directly in kilocycles and meters. The dynamic loud-speaker, comprising a five-inch cone in a miniature cabinet, actually gives the receiver better fidelity than the average receiver of ten years ago, especially on the human voice. All these features have been introduced and commercialized in the last decade.

The progress realized in 1936, while admittedly small as compared with that of ten years, has been of such a large order that the work of preparing this review has been easy in point of discovering a wealth of material. The only difficulty has been the selection of those developments which are not only important steps in the past year, but which may be expected to increase in their importance.

The Broadcast Receiver Industry

The number of broadcast receivers manufactured and sold in this country in the year 1936 has nearly passed the nine-million mark, as compared with six million in the previous year, which was then a record for all time.[3,4] The dollar values of sales has reached 500 million as compared with 300 million. This is rapidly approaching the all-time high of 600 million dollars recorded for 1929. One and one-half million of the past year's receivers have been sold for use in motor-cars.[4]

There has been no significant change of the total number of models and their average list price. The number of models introduced in 1936 is well over 1000, with an average list price[18] of about $65.

Published tables are available which list about 1200 new models of about seventy companies, with various features of each model. Nearly all of these companies are manufacturers.[5,9] Reference to these tables has been very helpful in preparing this review. Nearly all of these companies are handling socket-powered receivers, while only about half handle motorcar receivers and about half handle other types of battery-operated receivers for farm and portable use. The socket-powered models include many alternating-current—direct-current sets, but the receiver intended only for direct-current operation seems to have vanished from the market. The alternating-current—direct-current lines now include not only the table models of the lowest price class, but also console models up to seven tubes. Only

about one quarter of these companies still make any tuned radio-frequency receivers, and these are only in the lowest price class.

From the tables mentioned, it is possible to describe a table model and a console model representative of the average of these classes.[18] The typical console model is listed at $100 and includes nine tubes. The power output is seven watts to drive a loud-speaker with an outside diameter of eleven inches. The typical table model is listed at $40 and includes six tubes. The power output is one watt to drive a loud-speaker six inches in diameter.

Among the sales features, the most prominent are still linked with eye appeal. There is an unusual variety of cabinet designs. The use of large elaborately calibrated dials has increased. In a few models, a magnified image of a section of the dial is projected on a translucent screen. A few other models have "telephone-dial" selection among a small number of stations chosen in advance. Visual tuning indicators are used by three quarters of the companies, the eye type of tube being the most common form of indicator.

Engineering Features of Broadcast Receivers

The introduction of automatic frequency control in American broadcast receivers was an outstanding development of 1936 in the practical application of radio engineering. The need for such an improvement gradually increased with greater selectivity and resulting difficulty of tuning with sufficient precision. The need became acute with the wide use of all-wave receivers whose tuning required very critical adjustment. This improvement is intended to make the manual tuning adjustment less critical in the same manner that automatic volume control simplified the operation of the manual volume control.

The idea of automatic frequency control is old. It has been used for some time in transatlantic radiotelephone circuits and in other specialized apparatus. It was used a year earlier in broadcast receivers manufactured by a British company. Its use in American receivers was delayed mainly by the economic depression, because its effective utilization requires from one to three extra tubes, and also requires maintaining the alignment of all intermediate-frequency tuned circuits with greater precision.

The feature which is common to all the automatic frequency control systems now employed in American receivers, is the simplification of the frequency-discriminator circuits.[39,40] A coupled pair of tuned circuits has its primary and secondary voltages combined to produce the required asymmetrical frequency characteristics. This method relies

on phase difference and therefore differs from the method of detuned circuits employed in the earlier British receivers.

The actual frequency control by an auxiliary tube is effected on the superheterodyne beating oscillator, and therefore is effective with respect to all the intermediate-frequency tuned circuits but not with respect to the tunable circuits ahead of the modulator or converter. This is one reason for limiting the amount of control to a very small number of signal channels, or even to the width of only one channel.

In the past year, about six companies have adopted automatic frequency control in their most expensive models. Two of these companies utilize this improvement to permit the use of "telephone-dial" selection of a few chosen stations. The same principle in the form of "cash-register" selection was introduced several years ago but it was discontinued in the meantime because it was unsuccessful when receivers became very selective and did not yet have automatic frequency control. Telephone-dial selection has now become entirely practical in the standard broadcast band.

In automatic frequency control as applied to the tunable oscillator of a superheterodyne receiver, there is a difficult problem in securing a uniform range of control over the entire tuning range. One company is using a double superheterodyne to obtain a simple solution. The frequency control is applied to the second beating oscillator, which is not tunable, and the resulting range of control is therefore uniform and independent of the tuning, on all tuning ranges of the receiver.

The past year has seen a major trend in the improvement of fidelity by the much wider use of variable selectivity obtained by manual adjustable expanding selectors. In general, greater selectivity is alternatively made available for use under adverse conditions such that even average fidelity cannot be employed. About half of the companies now use variable selectivity in their best grade of receivers. The variation of inductive coupling in one or more of the intermediate-frequency transformers has almost completely superseded other means for expanding the band width. The greatest refinement of adjustment is secured by moving coils to obtain continuous variation of band width, permitting the user to choose the optimum compromise between the desired fidelity and the undesired interference and noise. The alternative method is a two-point or three-point switch for connecting or disconnecting fixed coupling coils. If a three-point switch is used, two degrees of expansion are secured by expanding first one and then two of the intermediate-frequency transformers. The practice of combining the selectivity control with the high-audio tone control has continued. The usable fidelity of the better receivers is now limited

more by local noise and interference than by the characteristics of the receivers.

The introduction of metal tubes in 1935 was followed by the so-called "metal-glass" and "octal" glass tubes to meet requirements during the period of insufficient production of the metal tubes. The metal-glass tubes have disappeared, but there has been increasing use of the octal tubes, which are glass tubes with octal bases like those of metal tubes. The use of glass tubes with the old base has declined rapidly. The use of metal tubes has increased until nearly half of the companies use metal tubes in most of their models. The octal tubes are now used in all their models by two of the largest companies. Most of the commonly used types of tubes are now available in both metal and octal styles. The choice between these two styles is therefore mainly a question of company policies. The type numbers of octal tubes have a "G" added to the number of the corresponding metal tube. The duplication of similar types of receiving tubes in different styles has caused the total number of type numbers to double in the course of the year. Multiple-unit metal tubes have been introduced in sufficient variety to compete with the old glass and octal styles. All of the new types intended for alternating-current operation have six-volt heaters or filaments to fit in with requirements of alternating-current—direct-current receivers and motorcar receivers, as far as possible.

The increasing use of ballast lamps and resistors in vacuum tube mountings has lead to the production of a great variety of such tubes. About fifty types have been made available. About half of the types are in metal-tube envelopes, thereby avoiding excessive illumination from the filaments. Ballast lamps are connected in series with the heaters or filaments of vacuum tubes and dial lamps, especially in alternating-current—direct-current receivers or battery-operated receivers. Considerable benefit is obtained from some types by virtue of their current regulating action. About half of the companies are now using ballast tubes in some of their models.

There has been increasing use of the type of audio power amplifier tube which has in one envelope a low power triode driving a high power triode.[47] One company uses this tube in all models.

The past year saw the introduction of beam amplifier tubes, the first commercial tubes to employ electron beams for increasing the amplifying efficiency.[45,46,49] The beam amplifier tubes are already used in the power output stage by at least seven American companies. The output available from two tubes in a push-pull stage is as high as forty watts.

The introduction of the beam amplifier was followed by recom-

mendations for the use of stabilizing feedback in the last stage to reduce distortion of all kinds, especially harmonic distortion at high power levels.[45,48,50,51] An important added advantage is the electrical damping of the loud-speaker diaphragm, which has formerly been obtained only by triodes having relatively low plate resistance. At least two companies are now using this feedback in conjunction with beam amplifiers.

The beam indicator tube brought out in 1935 for visual tuning gave new life to the feature of tuning indicators. This type of tube has been made available in Great Britain and several slightly different variations have appeared in this country. About two thirds of the companies now use these beam tubes for visual tuning indicators.

Two of the largest companies, among others, continue to use exclusively shadow meters as tuning indicators. One of these companies employs a circular shadow whose diameter decreases to a minimum as the receiver is tuned to resonance.

A novel form of visual tuning which appeared in the past year is the color indicator used by one of the large companies.[12] The illumination of the entire dial is changed from red to green as the receiver is tuned to resonance. Therefore the operator sees the tuning indication on any part of the dial without taking his eyes off the tuning scale. The change of color is accomplished by dial lamps arranged in two sets connected in series. There is connected across one set of lamps an iron-core reactor whose impedance is controlled by direct current in an auxiliary coil on the same core.

There has been much greater use of the frequency bands above and below the "all-wave" frequency range of 0.54 to 18 megacycles.[54] Great interest has centered on the "ultra-high-frequency" band of about 20 to 60 megacycles. Major improvements have been made in the performance in this band, which is now used by at least fifteen companies. The "weather band" of about 150 to 400 kilocycles is now used by at least twenty-three companies. About half of all models cover the all-wave range. Nearly all models use an intermediate frequency in the neighborhood of 460 kilocycles. Most of the companies now use 456 or 465, the latter having been sponsored by the RMA Committee on Broadcast Receivers. Three of the largest companies use 450, 460, and 470, respectively.

There has been a steady increase in the use of iron-dust cores in sharply tuned circuits. At least four American companies and several European companies use iron cores in intermediate-frequency coils. There is wide use of iron cores to improve the efficiency of the tuned input circuit of motorcar receivers, since the antennas pick up such a

small signal voltage. One of the large companies has gone to movable iron cores for adjusting the alignment of radio-frequency and intermediate-frequency circuits, supplanting part of the adjustable trimming condensers otherwise required.[12,54] The remaining trimming condensers are coaxial air condensers chosen for maintaining permanence of alignment.

The increasing radiated power of broadcast transmitters has intensified the tendency toward overloading the first and second tubes of the receiver. Highly selective trap circuits are made by several companies for connection between antennas and their receivers in the immediate neighborhood of powerful transmitters. The suppression frequency of the trap is made adjustable for tuning exactly to the offending signal.

The all-metal bodies of motor cars developed an antenna problem which led in 1935 to the use of undercar antennas. In the past year, there have been developed elevated antennas for motorcars, which have some advantages in performance and are being used in large numbers. One of the new designs takes the form of an elevated rod or "fish pole" fastened near the windshield and adapted to be folded down when desired. The other is a horizontal rod rigidly supported just above the car roof, a few inches above the center line. Shielded lines between antenna and receiver are generally employed.

The use of noise reducing doublet antenna systems has been increasing.[58] At least five companies are including switching arrangements in the receiver input circuits, such that the balanced transmission line from a doublet antenna can be switched directly into the input transformer. An unusual contribution in this field is the spider-web antenna, which is an assembly of three or five doublets in the vertical plane, all connected across the same transmission line.[12] The individual doublets are resonant at frequencies of 6, 12, 18, 35, and 60 megacycles, the 6- and 35-megacycle doublets being loaded by inductance at the line terminals. The three longer doublets are horizontal and the two shorter doublets are vertical. The assembly is adapted for suspension between two points 37 feet apart. Noise induction is secured only over the frequency range in the neighborhood of the natural frequencies of the doublets.

The past year saw the first use in commercial broadcast receivers, of a device for limiting sharp impulses of noise.[12] One of the large companies has added a diode limiter in conjunction with a diode detector, for limiting any impulses greater than signal peaks corresponding to unity modulation. This subject was revived by recent publication relative to various circuit arrangements for limiting or even quiet-

ing any noise impulses of great amplitude and very short duration.[28,35,37,59,64]

Volume expansion for increasing the dynamic range of music is employed by three companies. Two of these companies use electronic means of well-known properties.[53] The other company connects a lamp filament across a section of the output transformer secondary, and relies on the varying temperature and resistance of the lamp to cause volume expansion. Two other companies are employing electronic volume compression to restrict the range of loudness, if desired by the listener.

In the loud-speakers of the new models, the main tendency is toward acoustic treatment of the cabinets to remove their objectionable properties and to improve the radiating efficiency, especially at the very low frequencies. Such improvements are designed also to damp the loud-speaker and thereby to minimize low-frequency transient vibrations. Another tendency for the same purpose is toward the use of supporting frames of large diameter, designed to set back the cone and thereby to load more effectively the front side of the loud-speaker.

The most elaborate audio system is found in a 37-tube receiver.[52] There are three individual audio power amplifiers for handling respectively the low, medium, and high divisions of the audio-frequency range. The corresponding sound radiating systems comprise respectively an 18-inch cone, two 12-inch cones, and three small horns. A crystal microphone is included to permit using the receiver as a public-address system.

The intensive development of vibrators during the past few years has culminated in a complete and satisfactory line of mechanical interrupters for converting direct current from batteries to alternating current of higher voltage.[65] Some of these interrupters have auxiliary contacts for rectifying the high voltage. Vibrators have come into universal use in motorcar receivers, which are operated from six-volt storage batteries.

Automatic selectivity control has been the subject of important developments not yet found in commercial receivers. Stabilizing feedback has been utilized to expand the band width of the selective circuits, the amount of expansion being determined by the grid bias.[43,44] The expanding characteristics have the same shape as those of a pair of tuned circuits with variable coupling or symmetrical detuning. The preferred arrangements have the expansion accompanied by reduction of amplification so that the same grid bias can be used to secure both automatic volume control and automatic selectivity control.

Other Classes of Receivers

Television receivers have been made and sold commercially during 1936 in France and Germany.[16,17,24,25] Their use in England and the United States has been on an experimental basis. A number of experimental receivers have been placed in regular operation, especially in the neighborhood of New York and Philadelphia, receiving from the experimental television transmitters.

The progress which has been made in the design of communication receivers for the fixed and mobile services has been published to such a small extent that it cannot be summarized. The published developments feature improvements in remote control, noise impulse limiting, and single side-band reception. Superregeneration has been placed on the market for the first time, in a police car receiver.

Experimental reports have related to subjects such as diversity reception and frequency modulation. An ultra-high-frequency receiver has been designed, using coaxial conductors of adjustable length in place of tuned circuits.

Amateur receivers have been made commercially available with all the improvements of broadcast receivers and with added special features. At least five companies have been featuring amateur receivers of advanced design. The special features include separate oscillators and crystal filters for use in beat reception of code signals, two radio-frequency amplifier stages ahead of the superheterodyne modulator, and noise impulse limiters. The list prices are about $100 to $500.

The Testing of Receivers

There has been steady but not spectacular improvement in the field of testing equipment for radio receivers. An outstanding improvement of the year is the introduction of a directly calibrated frequency dial on commercially available standard signal generators of the better grade. This feature, combined with coil switching and amplifier modulating, has been embodied in an economical design with operating characteristics which are exceptionally good in most respects.[66]

The improvement of the characteristics of radio receivers depends almost entirely on the ability to measure and to specify these characteristics. This is proved by the inferior or doubtful characteristics of loud-speakers, largely because their testing involves complicated apparatus and procedures. Major contributions are being made by the standing committee of radio organizations, in setting up standardized testing procedures and recommended practice for radio apparatus. Radio receiver committees for this purpose have been in action under the American Standards Association and the Radio Manufacturers

Association, as well as the Institute of Radio Engineers. The Institute committee has nearly completed a revised and enlarged report to supplant their last preceding publication of 1933. This report deals mainly with test procedures, which have been studied thoroughly in the past year.

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RADIO PROGRESS DURING 1936

Part IV—Report by the Technical Committee on Television and Facsimile*

THE field of television and facsimile communication differs notably from other fields of radio in that its commercial adaptation has not been far advanced. A preponderant proportion of the progress in this field is the result of experimental work, carried on by a substantial number of organizations and individuals, under conditions which do not permit the results achieved to become immediately and widely evident.

The experimental nature of the field results in diverse methods of accomplishing a given objective, and the lack of field experience makes difficult the accurate judging of the effectiveness of the results achieved. A large group of workers were invited to contribute notations on their developments during the past year. Their reports are presented herewith. They have received the smallest amount of editing which it was felt would put them in satisfactory and understandable form. The absence of a report from any organization active in the field means only that no report was submitted.

Television is not as yet an established commercial system of communication in this country. The Federal Communications Commission has maintained the licensing of transmitting stations on a strictly experimental basis. As a method of crystallizing engineering opinion, a substantial volume of data was compiled by those interested in television and submitted to the Federal Communications Commission in the form of testimony at an informal hearing arranged by that body.

As in the case of television, the Federal Communications Commission has continued, on an experimental basis, the licensing of facsimile broadcast stations. However, commercial point-to-point communications of this type over wire lines has been authorized by the Commission. Picture services between New York City and Chicago and New York City and Buffalo were inaugurated. These services are in addition to the transatlantic services which were already in existence at the start of the year and have continued without essential change. The use of the telephone lines for phototelegraph services has continued and was advanced by the development of portable transmitting equipment for use in conjunction with the standard telephone service.

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There follow herewith the reports which have been submitted to the committee. The material on facsimile is given first and is followed by an outline of the developments in television.

FACSIMILE

Bell Telephone Laboratories

During the past two years, the Bell System has inaugurated a new type of private line telephotographic service by setting up a twenty-six station nation-wide network for the Associated Press. This service utilizes sending and receiving machines of the latest type which can handle pictures of various sizes up to 11×17 inches and are capable of daylight operation. Photographic prints or paper copy are transmitted directly and are received as a negative on film. The material is mounted on cylinders and transmitted at the rate of one inch axially per minute, the maximum size requiring seventeen minutes, with a scanning structure of 100 lines per inch. The line circuits, specially modified for picture transmission, are so arranged that any station can send a picture to any or simultaneously to all other stations. The signal frequencies vary from zero to 1000 cycles and modulate a carrier of 2400 cycles, the upper side-band being suppressed to keep within the frequency requirements of the lines.

Finch Telecommunications Laboratories

Developments have been completed along several lines of endeavor in the communications field, focused mainly on the practical development of equipment commercially useful for naval, military, government, and news gathering agencies. Such designs naturally feature extreme simplicity, portability, and utility in making use of any available interconnecting facilities. In this line there have been completed the following:

1. A lightweight printing telegraph utilizing wire or radio channel which has found use in aircraft, police, mobile, and news reporting work.
2. Development of new types of electronic tubes and associated circuits for the practical elimination of mechanical devices in several applications.
3. Tests on a portable telephotographic system which is adapted to send newspaper photographs accurately and quickly over any interconnecting system.
4. Progress in application of electron-ray methods to the high speed transmission of facsimile matter.

5. Improvements in the matter of simplification of a facsimile system not requiring photographic development of received prints, and particularly adapted for the home reception of such matter during inactive periods of the broadcast schedule.

6. Developments of a system of ultra-short-wave local intercommunication system for reporting service.

Fultograph, Inc.

Fultograph, Inc., is an organization for the development of the facsimile system of Otho Fulton, and has been active in 1936 primarily in equipment development and in radio facsimile transmission and reception studies.

In the field of transmitters, new transmitter control equipment of compact type has been developed for use with existing broadcast transmitting equipment. Portable transmitter controls have also been constructed.

Receiver development has been carried forward. A portable receiver for aviation purposes has been constructed and successfully tested.

Several new types of start-stop mechanism, both electromechanical and electrical in nature were produced and function effectively.

Preliminary experimental work in the production of a continuously operating receiver has been carried forward.

Transmission experiments on short waves over distances of several hundred miles show the capability of the equipment in successfully transmitting facsimile material between cities. Material thus transmitted has been automatically relayed on ultra-short waves and recorded with substantially identical facsimile quality.

Facsimile communication between automotive vehicles, and between land stations and airplanes in flight was studied during the year, and such studies showed the adaptability of facsimile communication to these purpose.

Radio Corporation of America

The development of RCA facsimile systems was continued by its manufacturing and communications service.

On RCA Communications' transoceanic and transcontinental services, the normal long-distance radio multipath distortion limited operation to speeds in the range 1.5 to 2.3 square inches per minute. The New York to Philadelphia radio relay circuit using experimental Federal Communications Commission frequency assignments in the 85- to 105-megacycle band devotes two channels to black-and-white facsimile service. This circuit uses two intermediate relay stations.

Reflected light photoelectric scanning, on-off keyed carrier, and visual carbon recording technique are employed. Channel speed is 8.5 square inches per minute, line advance 120 per inch, synchronizing base 480 cycles, drive accuracy one part in million.

The Federal Communications Commission granted, under a general experimental license, the use of frequency 38.6 megacycles for survey of lower Manhattan area by facsimile type system. This employs revolving prism controlled photoelectric scanning of moving subject slip, on-off keyed carrier modulation of transmitter, and visual carbon slip recording technique. The approximate intelligence handling speed is 50 to 55 words per minute with linear operating speed of 36 inches per minute, scanning 60 strokes per second, and average subject type 10-point size.

Radio Pictures, Inc.

The general objective of the development work during 1936 has been to provide a complete system of facsimile broadcasting capable of satisfactory operation on the frequencies made available for this type of service by the Federal Communications Commission, and comprising terminal apparatus that is neither unduly complicated nor expensive, and the maintenance of which requires service only of the order now associated with aural broadcast activities.

In the absence of any generally accepted standard of transmission, facsimile development has been based upon line scanning of 100 per inch and 100 per minute, and those recorders which have been put into service have been adapted to reproduce three columns of newspaper text or an equivalent of pictorial subject matter. Both transmitting pickup and recorders as now used are of the continuous-feed direct-viewing type, the image appearing at the receiver in a permanently recorded form at the same rate and in the same aspect ratio as the original transmission.

The recording medium used is a sensitized paper available either for black-and-white reproduction, or for sepia, as may be desired, for either text, so called black-and-white, or half-tone pictures.

Western Union Telegraph Company

During 1936, the Western Union Telegraph Company used facsimile systems for handling a portion of its regular traffic between New York and Buffalo and New York and Chicago. A third facsimile circuit is used for handling the traffic between the New York main office and a city branch office.

The machines at both the transmitting and receiving ends are

equipped with racks which serve as magazines for transmitting and recording drums. The rack at the transmitting machine is filled with drums upon each of which a message to be transmitted is held by easily removable spring garters. The rack at the recorder is similarly equipped with a number of drums provided with recording paper. In operation, the transmitting machine merely scans that portion of the blank upon which a message is written and then automatically substitutes the next message. Whenever a message is thus changed at the transmitting machine, the recorder automatically ejects the complete message and feeds a drum with a new blank into the machine.

The facsimile receiving blank is characterized by its reddish color. As the signals are received, the characters appear in black on this paper. A permanent record is produced and no processing of the paper is required after recording.

TELEVISION

RMA Committee on Television

During this year the RMA Television Committee, drawing together active interests in the television field, agreed upon the recommended television standards which follow:

STANDARDS RECOMMENDED BY THE RMA TELEVISION COMMITTEE

1. Frequency allocation:	
Lower limit	42 mc
Upper limit	90 mc
An experimental band starting at	120 mc as the lowest frequency
2. Channel width	6 mc
3. Spacing between television and sound carriers	3.25 mc (approx.)
4. Relation of sound carrier to television carrier	Sound carrier higher in frequency
5. Polarity of transmission	Negative
6. Number of lines	441
7. Frame frequency	30 per second
Field frequency	60 per second, interlaced
8. Aspect ratio	4:3
9. Percentage of television signal devoted to synchronizing signals	Not less than 20%
10. Synchronizing signal:	
(a) Duration of horizontal blanking signals	Approximately 1/10 of the time to scan one line, 1/10th of the time to scan one field, respectively
(b) Position of synchronizing impulse in regard to blanking signal	At leading edge (approx.)

The above standards, with the exception of No. 10, which has recently been added, were presented to the Federal Communications Commission at the June 15th hearings in Washington.

Bell Telephone Laboratories, Inc.

During the past few months a coaxial cable has been installed by the Bell System between New York City and Philadelphia, equipped with amplifier stations and terminal apparatus to form a wide-band

transmission system capable of 240 simultaneous telephone conversations. In as much as this system transmits a 1000-kilocycle band it has possibilities for transmitting television images. Special terminal and intermediate apparatus for experiments in such utilization of the wide-band possibilities of the cable are under development. In the present experimental setup the intermediate amplifiers would be capable of transmitting a television video band of about 800 kilocycles, which corresponds approximately to 240 lines per frame, 24 pictures per second.

Don Lee Broadcasting System

During 1936 the Don Lee Broadcasting System, Los Angeles, completed the development and construction of a high definition system of television.

The images are sequentially scanned with 300 lines and are repeated twenty-four times per second. This standard was adopted in 1935 in view of the power system idiosyncrasies in Southern California. Of the two million persons residing within fifty miles of the transmitter, W6XAO, nearly half are served by electric power of fifty-cycle frequency, while the other half are served by power of sixty-cycle frequency. There are no plans to alter this condition. It is understood that an interlaced method of scanning will not function at its best on a power system of different frequency than that employed at the transmitter.

Daily technical tests are made with the complete system. A receiver has been located near the transmitter and also at 3¾ miles, behind two hills. High vacuum sweep circuits are used with a selecting amplifier method of synchronization. The synchronization is not affected when the number of lines at the transmitter is purposely changed by five per cent from the normal value of 300. Interference, as from automobiles, must be 300 per cent greater than the received signal in order to affect the synchronization.

The test at the 3¾-mile location have been conducted with a transmitter-power—receiver-distance figure of 33 watts per mile. If the intervening hills are considered as effectively doubling this distance, the figure becomes 17 watts per mile. This procedure is indicated by the reception results obtained by an independent observer located on level ground 6¼ miles from the transmitter.

Public demonstrations have been held since June 4, 1936, for as long as four hours per day. The stability of the apparatus has been proved by these demonstrations. Except for one rectifier tube and one transmitter tube replacement all the equipment has been in service for nearly a year.

Farnsworth Television, Inc.

In development of the Farnsworth System during 1936, several new devices have been evolved which together with engineering advances have improved the practical and entertainment aspects.

Adaptation of the multipactor tube to the image dissector and to video amplification have enabled the reproduction of television images of finer detail. At the same time, it has been found possible to reduce the illumination intensity formerly required for television pickup, thus allowing greater latitude in subject material.

A new experimental television studio has been equipped with the latest types of television apparatus, including several cameras for film indoor and outdoor pickups. This has been operated experimentally with 343-line interlaced images for some months and is now being altered to conform to the recently recommended standards of the RMA for 441-line scanning with thirty frames per second, interlaced. Considerable experimental work has been done on problems of illumination and program technique.

Simplicity of construction and operation has been stressed in development of receivers. 5×7 inch images of an excellent black-and-white contrast are produced by present receivers, and others are under development for larger images.

A construction permit was recently issued to this company for a television experimental station. A 150-foot tower has been erected adjacent to the new studio, on elevated land near the northern boundaries of Philadelphia. Construction of the television transmitter is already in progress. It is intended to operate at a carrier frequency of 62.75 megacycles, with 2.5-megacycle side bands, and the sound carrier at 66 megacycles. The ultimate power for the video carrier is to be four kilowatts. It is planned to place this station in operation in the early part of 1937 for the conduct of field tests in the Philadelphia area.

Philco Radio and Television Corporation

The Philco research department has been engaged in television research during the past eight years. Their activities have included the development of systems capable of transmitting radio pictures from studio, films, and outdoors.

During 1936 extensive field tests have been in progress in Philadelphia and vicinity. These tests were carried out with a 345-line, 30-frame, interlaced television system, the transmitter frequencies being 51 megacycles, (picture) and 54.25 megacycles (sound).

In order to permit modulation frequencies up to 2.5 megacycles

to be transmitted successfully, a special type of modulation was developed. Radio receivers capable of utilizing this wide frequency band to produce high definition pictures were also developed.

Philco has produced 12-inch picture tubes giving a substantially black-and-white picture, and has used them in field tests and in a demonstration to the press on August 11, 1936.

In order to obtain greater detail than is afforded by a 345-line system, Philco has advocated communication channels six megacycles wide. To conform with the new RMA Standards, the system is now being converted to operate on 441 lines, 30 frames, interlaced.

A new type of synchronizing signal incorporating a "narrow vertical," that is one less in duration than half the time of scanning one line, has been devised and put into operation successfully.

To obtain greater field strength throughout Philadelphia and vicinity a new tower to support the transmitting antennas has just been installed. Field tests, using the new 441-line system, will shortly be resumed.

Radio Corporation of America

During 1936 RCA continued active research on high definition all-electronic television. This research has continually provided improved electronic devices and methods which have been progressively applied to experimental systems in the laboratory and field. This step-by-step program has been an important phase of the RCA attack on the complex television problem.

During 1935 work was undertaken on an experimental field test system in New York so that practical experience could be obtained on technical problems, apparatus, programs, and considerations of television system standards. Tests of this RCA system began on June 29, 1936, with an organized program of experiments between a high power transmitting station fully equipped for studio and film programs and receivers in a number of homes throughout the New York area. Live talent and motion pictures have been successfully transmitted. Observations and measurements have been made on the transmissions. Good reception has been obtained twenty-five miles from the transmitter, and in one favorable location, because of the extreme height of the transmitter antenna, consistent reception has been had at forty-five miles.

The television studios are located in the RCA Building with complete facilities for direct pickup and film programs. The video signals are transferred to the transmitter in the Empire State Building either by coaxial cable or radio relay. The video and audio transmitters are located on an upper floor of the Empire State Building, with a com-

mon antenna at the very top. The video transmitter carrier frequency is 49.75 megacycles and the audio transmitter carrier frequency is 52 megacycles. The radio relay channel between the RCA and Empire State Building operates on 177 megacycles.

The experimental system uses 343 lines per frame, interlaced,with frame frequency of 30 per second and a field frequency of 60 per second. Synchronization at the receivers is by transmitted impulses. The horizontal and vertical synchronizing impulses are of the same amplitude using wave shape selection.

In co-operation with the industry RCA has recommended to the Federal Communications Commission the adoption of standards including images of 441 lines and a video-audio carrier spacing of approximately 3.25 megacycles. The RCA field test system will be changed to conform to these recommended standards at a convenient time in the experimental program.

Good progress has been made in studying the system and its functioning under field conditions. Data have been obtained on field intensities and noise levels. Engineering studies have been made on problems relating to program technique. These tests, to date, have confirmed the soundness of the technical fundamentals of the system. They point the way to accomplishment of the prime objectives: first, to develop suitable commercial equipment for transmission and reception; second, to develop a suitable program service and the accompanying network syndication; third, to develop a sound economic base to support a television service.

Radio Pictures, Inc.

A substantial part of the work in television during the past year has been in extending the capabilities of the cathode-ray tube in high definition transmission. This has included a study of general principles underlying the theory of electron optics with particular reference to adapting thin lens electrooptical systems to television reception. Means have been discovered to mitigate undesirable optical distortions such as the "keystone," "barrel," and "lozenge" effects. Cathode-ray tubes of increased sensitivity have been made, and investigations of screen materials for increased brilliance, and the study and test of circuit designs for improving the quality of received pictures have been continued.

With the reallocation in visual broadcast frequencies, experimental transmissions in the 2000- to 2100-kilocycle band were discontinued, and regularly scheduled experimental broadcasting will be resumed in the ultra-high-frequency bands now available as soon as new transmitting equipment is completed and tested.

Foreign Developments

During 1936 there has been considerable activity in television in several foreign countries, much of which has had as its objective the trying out of high quality systems on a much more extensive scale than heretofore. These plans not only cover the technical phases but in some cases go into the important question of program production which must be solved before television is put on a commercial basis. In general, the foreign art is moving toward pictures of higher resolution although there is no agreement as to the number of lines per picture that will ultimately be desirable.

England

The British Broadcasting Corporation opened a London transmitting station at Alexandra Palace on November 2. Two companies, Baird Television and Marconi-E.M.I., are responsible for the two systems used, which have been designed to permit considerable flexibility in the tests. The pictures, for both systems, have an aspect ratio of 4×3 and are broadcast on a carrier frequency of 45 megacycles, the associated sound being on 41.5 megacycles.

The Baird Company uses 240 lines, 25 pictures per second, with sequential scanning, while Marconi-E.M.I. employs 405 lines, 25 pictures per second, interlaced, to give 50 frames per second, each of $202\frac{1}{2}$ lines.

The Baird system uses two pickup devices. One is of the so-called "spotlight" type, in which scanning is by means of a beam of light played over the subject. It is restricted to close-up studio work. The other system uses the "intermediate film with scanning disk" method, in which a modified motion picture camera takes pictures on film which is immediately developed and then scanned by means of a disk.

The Marconi transmitter uses a cathode-ray type pickup for both direct and film transmission.

Both systems use the same sound transmitter and vertically polarized radiators which are mounted on a 300-foot steel mast. The sound transmitter is rated at "three kilowatts at 90 per cent modulation" and will handle audio frequencies from 30 cycles to 10,000 cycles. The picture transmitter is given a "17-kilowatt peak" rating.

Several British firms are active in producing receivers, most of which utilize 12-inch cathode-ray tubes although some are as large as 15 inches in diameter.

Scophony, Limited, is also working on a form of receiver which is intended to provide the projection of pictures of adequate size and brightness for viewing by large groups of people.

Germany

During 1936 broadcast television was carried on by the Post Office and eleven viewing rooms established in Berlin for public demonstrations. The transmission is from a station at Witzleben operating on about seven meters. Both film reproduction and direct television using intermediate film have been employed. A portable transmitter was used for experimental transmission from the Olympic games.

The Post Office has installed a coaxial cable between Berlin and Leipzig which renders television services between specially designed sets in each city on a toll basis. Revolving mirrors are utilized for 180-line, 25-frame pictures.

Telefunken demonstrated pictures about 3×4 feet projected from a small cathode-ray tube.

Although little or no attempt has been made to commercialize receiving equipment, a number of German firms have produced, for exhibition, cathode-ray type receiving sets. The present standard of transmission is 180-line pictures including interlaced scanning. Electronic cameras have made their appearance.

Other Countries

One experimental station is said to be in operation in Australia, the system being a duplicate of the prior British system providing 30-line pictures at a rate of $12\frac{1}{2}$ per second. It is located in the Brisbane Observatory Tower and operates on 151 meters.

The State Broadcasting Service of France has two experimental transmitters working in Paris, one of which transmits 60 lines at 25 frames per second on 180 meters and the other 180 lines, 24 frames per second on a wave length of seven meters. The accompanying sound is from a medium wave transmitter. Disk scanning is used. A new 10-kilowatt television transmitter is being built at the Eiffel Tower.

The Philips Laboratories at Eindhoven, Netherlands, has experimental transmitters for sound and television operating at 43.2 and 41.2 megacycles. Both 180- and 360-line pictures, at 25 frames per second, have been used. A cathode-ray camera has been developed and is being used experimentally. Announcements have been made of receiving sets capable of receiving 240-line and 405-line pictures interchangeably.

The Italian Broadcasting Company has set up a research board at their Rome station for the purpose of engaging in television work, but no service to the public is being undertaken. Several laboratories have been experimenting for some years and one has given exhibitions at various fairs.

Although considerable experimental work on different systems is being conducted by various laboratories in Japan, no service is being rendered to the public.

The Swedish Radio Company has an experimental station of approximately 400 watts and utilizes a system with mechanical scanning producing 240-line pictures. No public service exists.

In the U.S.S.R. it is reported that regular low definition programs are being broadcast from Moscow on long-wave transmitters for both vision and sound. Transmissions of specially selected films, concerts, and short scenes are made during the night hours. The pictures are broadcast at 30 lines per frame, transmitted 25 frames per second.

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RADIO PROGRESS DURING 1936

Part V—Report by the Technical Committee on Transmitters and Antennas*

THIS report is based largely on publications which have appeared during the year. At the end is given a list of typical papers. This list, however, does not include all of the important articles which have been published. The report contains a few items which are mentioned because of their timeliness in advance of their formal publication.

Transmitters

One important development[1] has to do with a fundamental principle in the operation of high power radio-frequency amplifiers such as might be used in a broadcast transmitter. In conventional amplifiers employing low level modulation, the efficiency of the last stage is limited to thirty per cent or so because of the necessity during modulation of doubling the amplitude at times of one hundred per cent modulation. All of the tube complement is used all the time, during silence as well as during modulation. In this new system, however only half of the tubes are used during silent periods and the circuit is adjusted for efficiencies of sixty to sixty-five per cent. When modulation begins, the positive peaks of modulation bring into play a second set of tubes which has previously been maintained inactive. Besides contributing a share to the total power this second tube unit makes it possible for the first unit to contribute more power without reduction of efficiency. This system differs from other methods of obtaining high efficiency in that it acts as a linear amplifier and is independent of the type of signal employed. For example, a single side band could be amplified as effectively as the usual amplitude-modulated wave of broadcasting.

A wider spread in the use of stabilized feedback and related methods of reducing distortion and noise is apparent this year.[2] This use of automatic correction has been employed in many equipments and has been used widely for the improvement of transmission characteristics in transmitters of earlier design. Such developments have been a powerful aid in achieving complete alternating-current operation without use of rotating machinery.

* Decimal classification: R350×R320. Presented before New York Meeting, January 6, 1937.

[1] Numbers refer to bibliography.

The general interest in class B and class C amplifiers is reflected in some seven papers in the PROCEEDINGS this year, four of which are to the credit of our engineering schools.

The cathode-ray oscillograph in this field, as elsewhere, is fast becoming indispensable. Interesting proposals include its use as a wattmeter,[3] and for the tracing of parasitic oscillations.[4]

Noteworthy developments have occurred in the manufacture of quartz crystals having low temperature coefficients.[5] The use of quartz crystals as elements in filters has been one of the developments in this field. Although frequency stabilization by means of electric circuits such as the low power factor resonant line has been a subject for development over a period of years by various investigators,[6] it may be worth noting that 1936 has seen the method employed in services in which the crystal has usually been favored. Thus, one company has had in operation this year two transmitters controlled by resonant lines and operated in transatlantic service. Routine measurements of frequency deviation made throughout the year have indicated that the performance is substantially equal to that of many representative peizoelectric controlled transmitters.

In general, transmitter frequency stability continues to undergo a gradual, but decidedly noticeable improvement. This tendency corresponds to the tendency toward greater selectivity in receivers used for short-wave telegraph circuits.

In the effort to guarantee strong signals under all conditions there has been placed in operation at Rocky Point a ten-megacycle telegraph transmitter capable of delivering an output of 200 kilowatts. In combination with its directional antenna it radiates toward the distant receivers the equivalent of 10,000 kilowatts in a nondirectional antenna. The high power stage employs four water-cooled tubes. The anode power supply is from a six-phase full-wave pool-type mercury-arc rectifier capable of delivering a continuous output of 300 kilowatts. One interesting feature is the type of compressed air variable neutralizing condenser, the largest one being capable of withstanding 100 kilovolts. Such condensers provide the requisite kilovolt-ampere rating within a fraction of the space that would be needed at atmospheric pressure and afford protection from flashover due to foreign matter. Another feature is the use of resistors and potentiometers of thyrite. The characteristic of this material by virtue of which its conductivity instantaneously increases with voltage brings about a considerable saving in power dissipation for a given value of voltage regulation and also permits the elimination of sources of grid bias in some intermediate radio-frequency amplifier stages.

In one new transmitter, any one of ten frequencies can be chosen by the twist of an automatic telephone dial. All frequencies are crystal controlled and the change is made by remote control switching of pretuned circuits.[7]

The general improvement in the larger vacuum tubes by all manufacturers has resulted in a decided reduction in tube-hour costs. There is a marked trend toward the use of water-cooled power tubes having filaments designed for heating by polyphase currents. The resulting reduction in the noise level assists in the elimination of direct-current motor generator sets. This improvement, together with other aids in noise reduction explains the growing trend toward complete alternating-current operation.

For general communication purposes and for amateur use there is a marked trend toward power pentodes. The line of tubes suitable for suppressor grid modulation is being extended, and along with it, the line of transmitters using this system.

The metal tube begins to be employed in transmitters. An interesting development by one manufacturer is a fifty-watt police transmitter using metal tubes throughout with the exception of the rectifier tubes.

During the year one organization has constructed a transmitter in which standard tubes designed for water-cooling have had their anodes soldered into tapered copper blocks which in turn are inserted in the tapered hole in a larger block provided with circulation of cooling fluid. The following advantages are obtained: (1) avoidance of boiling at the anode, giving freedom from scale deposit and increasing permissible dissipation; (2) change of tubes without opening the cooling liquid system; (3) reduced temperature rise of the liquid at the contact surface due to increased area permitting smaller volume of water flow, greater dissipation or the use of an antifreeze if water is used.

Mercury-pool rectifiers of the igniter type have been used experimentally for providing the high voltage supply for radio transmitters.[8] In this device the arc is struck each cycle by applying a properly timed voltage pulse to an auxiliary electrode dipping into the mercury pool. A five-ampere supply at 16,000 volts direct current has been obtained and there is said to be reason to foresee the development of such rectifiers to meet any high voltage, high power rectifier requirements.

During the year, the Federal Communications Commission has issued regulations establishing higher standards for all broadcast equipment than have been previously required. Better protection of personnel from dangerous potentials and the reduction of fire hazards have been featured in these regulations.

The development of transmitting tubes for use at ultra-high fre-

quencies foreshadows a general improvement in the transmitters in this range. Without these tubes, the transmitter designer has been unable to use many of the methods which have proved most important at lower frequencies. By co-operation between the designers of tubes and circuits the frequency limit of conventional operation is being raised. For example, the development of a double pentode and appropriate circuits for straightforward power amplification up to 500 megacycles has been recently reported.[9]

A transmitter having a power output capacity of forty kilowatts, corresponding to a ten-kilowatt completely modulated carrier, and operating between forty and sixty megacycles has been reported.[10] This work was done in order to determine what can be accomplished by using existing, commercially available tubes of the water-cooled type in a type C amplifier.

Television is covered in a different report but from the point of view of this committee, the installation of a complete television transmitting system operating under field conditions is a noteworthy development. The system in New York City uses a twelve-watt radio relay[11] operating on a frequency of 177 megacycles for the purpose of carrying the video program from the studio to the broadcast transmitter which is about a mile away. The latter, atop the Empire State Building, comprises video and audio transmitters each of eight-kilowatt output, which feed through coaxial filters to a common multiunit antenna. The difficulties in satisfactorily meeting the requirements are obvious once they are stated: A 1.5-megacycle band, negligible phase shift, satisfactory amplitude characteristic, low noise levels, and imperceptible cross talk between video and audio circuits separated 2.25 megacycles. In operation the system has given gratifying results.

An ultra-short-wave relay circuit between New York and Philadelphia has been commercialized this year.[12] The circuit provides for operation in both directions of three printer channels and two facsimile channels in addition to the terminal intercommunication and relay channels. Another circuit operating on approximately 100 megacycles is being used for the remote control from New York of shortwave transmitters located at New Brunswick. An eight-channel ultra-high-frequency radio link has been developed and is now in use between New York City and a transmitting station at Brentwood, Long Island.

The opening of the ultra-high-frequency bands has given frequency modulation a new opportunity by making wide bands available. It has been shown that with frequency modulation an important advantage can be achieved in respect to comparatively weak noises.[13] In experiments over long distances, it has been found that frequency modulation

is not useful where multiple path transmission is involved.[14] Different types of transmitters have been used recently in the production of frequency modulation. Among them is a successful embodiment of the method in which amplitude modulation is converted into phase modulation by introducing a ninety-degree shift of the carrier phase with subsequent frequency multiplication. If an inverse frequency equalizer is used in the audio input, this phase modulation of the altered signal is equivalent to frequency modulation of the original.[13]

Considerable progress was made during the year in the development of transmitting and instrumental means for sending down from unmanned balloons meteorological observations on upper air pressure, temperature, and humidity.[15] It is the hope that equipment of this kind will replace the use of airplanes in this service and that, moreover, it will make observations possible at greater altitudes and under all weather conditions. Through the use of ground direction finders, determination of wind direction and velocity also becomes a possibility. The service requires accuracy in keeping with that of present aerographs, a total load of the balloon not in excess of two pounds, an equipment cost no greater than the cost of an airplane flight which is about $25.00 and the recording of all information automatically at the ground station.

Antennas

Continued interest is being shown by many organizations in tower designs to give a current distribution best suited to increase the efficiency and the fading-free ranges.[16]

In the broadcast field there is a definite trend toward the use of antennas equal to or approaching the optimum electrical length of 190 to 200 degrees; that is, actual lengths somewhat greater than one-half wave length. This is resulting in a gradual improvement in broadcast station efficiency and an increase in the distance to the "fading wall." One interesting development is the shunt-excited radiator[17] which makes it possible to build these high antennas with the bases directly connected to the ground system. The inner conductor of the coaxial transmission line is extended through a series capacitor up to the tower at an angle of about forty-five degrees. The elevation of the connecting point need not exceed a small fraction of a wave length in order to match the low impedances of the coaxial line. No other terminating equipment is needed.

Where the heights of broadcast antennas are restricted an interesting development of top-loading makes a considerable increase in efficiency possible if the physical height of the antenna is at least 120 degrees.[18] The top-loading capacitance is in the form of a network of

conductors, similar to a large wheel, with its hub resting on top the tower but insulated from it. A series inductance at this point permits tuning over a wide range. The top-loading system does not radiate, but permits a control of the field pattern. Another form of this top-loading consists in sectionalizing the tower and connecting a tuning coil between sections.

During the past year there have been made several transmitter installations consisting of two radio transmitting plants utilizing a single mast type antenna for simultaneous operation. Typical of such systems is one in which the two channels utilize five and one kilowatts, respectively, with a frequency separation of ninety kilocycles. Although this type of system is not entirely new, its use seems to be growing.

The continued use of directional antennas has resulted in the introduction of standard phase shifting and current distributing equipment for obtaining a wide range of field strength distribution patterns. This class of apparatus not only permits a change in pattern to be obtained if the first pattern proves inadequate but also permits an automatic change in pattern for regional stations when shifting from the five-kilowatt rating in the daytime to the one-kilowatt rating at night. These arrays ordinarily take the form of simple two-element arrays because the cost of complicated systems is considerable and because the basic requirements are usually simple.

Considerable attention is being paid to broadcast antenna ground systems, particularly where radiating towers with wide bases are used. Buried wires immediately beneath such a tower lead to losses in the earth above the ground wires which may be eliminated by the use of an elevated copper screen. At one station for example introduction of a ground screen increased the radiated field eleven per cent at the optimum frequency of the tower, a condition when the effectiveness of a screen is greatest.

Increased attention is being paid to the antennas used in broadcast reception. Efficiency must be maintained over a very wide range of frequencies for satisfactory reception with "all-wave" receivers.[19]

In the ultra-short-wave field, the "turnstile" antenna is an interesting radiator of the horizontally polarized type which economizes energy by concentrating it in a horizontal plane but which is nondirectional in azimuth.

The antenna used for broadcasting television from the Empire State Building is built up of units which might somewhat inaccurately be described as triangular loop antennas. Being disposed in horizontal planes they are nondirectional in azimuth. The sides are actually

separately fed half-wave dipoles. Additional gain is obtained by arranging three of these units in a vertical tier.

In two-way systems, the concentric line type of filter has been employed for obtaining duplex operation with a single antenna. In one filter operating in the thirty to forty-two megacycle police band, sufficient discrimination against the local transmitter was obtained to permit a frequency separation of only four per cent.[2]

One form of antenna whose use in police systems is increasing is a modification of the three-quarter wave length J-shaped antenna in which the quarter-wave pair formed by the lower section is fed from a coaxial line whose outer conductor comprises the long leg of the J and which mechanically is simply a continuous metal pole. The lower section may be series or shunt excited; in the second case the shorter leg is connected directly to the main supporting pole. The strength and simplicity of these designs is leading to wide use.

New developments in the field of "wave guides" have led to an interesting contribution in the field of directional antennas. One form of wave guide is merely a hollow metallic pipe. It is found that there exist many modes of propagation for electromagnetic waves in such pipes, so that if the wave length is only made small enough the tube becomes in effect an electromagnetic "speaking tube." The analogy to acoustics can be carried still further, for if the tube is terminated in a horn formed by flaring out the end the horn becomes an effective electromagnetic radiator. Its directivity naturally depends on the dimensions of the horn and the type of wave existing in the pipe.[22]

From the point of view of the theory of radio wave propagation, a paper recently presented[23] is of great importance. Previously rigorous solutions have been given for flat *earths* having conductivity and dielectric constants actually found, or for *spherical* earths having infinite conductivity, but not for the actual case of spherical earths having the constants actually found. A rigorous and useful solution for this problem has now been found. The concept of a surface wave has long been used by the radio engineer in dealing with transmission along the earth. In a crucial experiment at ultra-high frequencies over fresh water the absence of a surface wave component was shown.[24] This result casts doubt on the significance of the surface wave concept in transmission over the earth. These and other results published this year indicate that we are approaching a sound understanding of the whole ground-wave problem.[25]

Space does not permit a discussion of the very considerable advances which have been made this year in understanding the sky wave.

The report on developments during 1935 mentioned the possibility

that regulations regarding clear channels might be changed to permit the use of power for broadcasting in excess of fifty kilowatts. The Federal Communications Commission held hearings in October, 1936, for the purpose of considering the effects of such change in regulations. Studies of the situation were presented as testimony for and against the proposed change, and these studies represent one of the year's technical achievements in the field of radio transmission. A larger amount of data on field coverage of various classes of broadcast stations is now on record than ever has been assembled before. The data are comprehensive, and it is with great interest that the industry awaits the results of the Commission's study.

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THE SURFACE WAVE IN RADIO PROPAGATION OVER PLANE EARTH*

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Summary—*The results of Weyl for radio propagation over plane earth are found to differ from those of Sommerfeld by exactly Sommerfeld's surface wave. Experiments conducted under conditions for which these two theories differ greatly are entirely consistent with Weyl's results and show that Sommerfeld's surface wave is not set up by simple antennas. Accordingly the Sommerfeld-Rolf curves are in error for all conditions for which the dielectric constant cannot be neglected.*

Introduction

In 1907 Zenneck[1] showed that a plane interface between two semi-infinite media such as the ground and air could support an electromagnetic wave which is exponentially attenuated in the direction of propagation along the surface and vertically upwards and downwards from the interface. Zenneck did not show that an antenna could generate such a wave, but because this "surface wave" seemed to be a plausible explanation of the propagation of radio waves to great distances, it was accepted.

When Sommerfeld[2] obtained a solution of the radiation from an antenna on the surface of the earth that contained a cylindrical surface wave which at great distances is analogous to the Zenneck wave, the case for the Zenneck wave seemed complete.

Later Weyl[3] approaching the problem in a different manner obtained a solution which did not explicitly contain this surface wave component. It appears, however, that he was of the opinion that his result was numerically equivalent to that of Sommerfeld. Van der Pol and Niessen[4] have obtained various expressions for the solution of this

* Decimal classification: R113. Original manuscript received by the Institute, September 28, 1936.

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[2] Arnold Sommerfeld, "Über die Ausbreitung der Wellen in der drahtlosen Telegraphie," *Ann. der Phys.*, ser. 4, vol. 28, pp. 665–736; March 16, (1909).

[3] H. Weyl, "Ausbreitung elektromagnetischer Wellen über einem ebenen Leiter," *Ann. der Phys.*, ser. 4, vol. 60, pp. 481–500; November 20, (1919).

[4] Balth. van der Pol and K. F. Niessen, "Über die Ausbreitung elektromagnetischer Wellen über eine eben Erde," *Ann. der Phys.*, ser. 5, vol. 6, pp. 273–294; August 22, (1930).

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K. F. Niessen, "Über die entfernten Raumwellen eines vertikalen Dipol-

problem, which have apparently been considered mathematically equivalent to those of Sommerfeld. The curves calculated by Sommerfeld[5] for the variation of the field with distance have been extended by Rolf[6] so as to cover all practical ground conditions. These curves have been accepted except for minor criticisms[7] of the approximations that necessarily had to be introduced in order to reduce the number of variables.

This apparently satisfactory state of the theory of radio propagation endured without question until recently. It is true that the experimental checks were not always good but this was considered a result of the inhomogeneities of the earth and irregularities of its surface. Whenever experimental values differed greatly with this theory it was under conditions for which the effect of curvature of the earth or the effect of the ionosphere could not be neglected.

Recently Norton[8] has pointed out that the Sommerfeld formula from which the Rolf curves were derived, does not agree with more recent formulas of van der Pol and Niessen[4] and of Sommerfeld[9] and he has published an empirical formula which does not agree with the Sommerfeld-Rolf curves. The writer[10] has pointed out that the results of Weyl are not in agreement with those of Sommerfeld and Rolf,

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[6] Bruno Rolf, "Numerical discussion of Prof. Sommerfeld's attenuation formula for radio waves," *Ingeniörs Vetenskaps Akademien*, Stockholm, (1929), and "Graphs to Prof. Sommerfeld's attenuation formula for radio waves," Proc. I.R.E., vol. 18, pp. 391–402; March, (1930).

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[9] Arnold Sommerfeld, "Über die Ausbreiting der Wellen in der drahtlosen Telegraphie," *Ann. der Phys.*, ser. 4, vol. 81, pp. 1135–1153; December 11, (1926). This paper is free from the error of Sommerfeld's earlier papers.

[10] Chas. R. Burrows, "Existence of a surface wave in radio propagation," *Nature*, vol. 138, p. 284; August 15, (1936).

but actually differ from them by exactly this surface wave in question. He also has found that Norton's results agree with those of Weyl. Since Norton has derived his results from a formula of van der Pol and Niessen, their formulas presumably agree with those of Weyl.

As a result of the realization that the mathematics contained an ambiguity, the writer on September 23, 1933, attempted to decide the question experimentally by measurements at Budd Lake, New Jersey, employing ultra-short waves. The results indicated that the water was too shallow to meet the requirements of the experiment, since the transmission resembled that over land instead of over fresh water. At that time an experiment over deep fresh water was planned which has recently been successfully carried out. The results prove conclusively that simple antennas do not generate a Sommerfeld surface wave. This is in agreement with recent theoretical work by Wise[11] and Rice.[12]

As an immediate practical consequence of this work we are able to say definitely that the attenuation curves given by Sommerfeld and Rolf are incorrect for all types of ground for which the dielectric constant cannot be neglected.

Experiment

When an attempt is made to determine which of the two formulas for radio propagation is correct, on the basis of previously available experimental data, several difficulties are encountered. First, the available data has been taken under conditions where the difference between the two formulas is small; second, the data have been taken under conditions where irregularities of the earth's surface are sufficient to produce variations in the received field strength of this order of magnitude. Third, the ground constants are not known by independent measurements with a sufficient degree of accuracy. All of these difficulties may be removed by making measurements on ultra-short-wave propagation over fresh water. Here the two formulas predict field strengths that differ enormously. The irregularities of the earth's surface are reduced to a minimum by making measurements over calm fresh water, the inhomogeneities are removed by employing deep water, and finally the dielectric constant of the water can be determined from its temperature and the conductivity by measurements in the laboratory.

Seneca Lake in New York state was chosen for these experiments

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because of its great depth. A wave length of two meters (150 megacycles) was chosen as a convenient ultra-short wave since apparatus was available for this wave length.

These experiments are divided into two parts; (1) a determination of the variation of the received field strength with distance, and (2) a determination of the variation of the received field strength with antenna height at a distance for which the predictions of the two formulas differ greatly.

Fig. 1—Experimental arrangement for determining the variation of the received field strength with distance.

Variation of Field Strength With Distance

Fig. 1 shows a picture of the experimental arrangement for determining the variation of the received field strength with distance. The receiver was located near the stern of a small motorboat which towed a rowboat containing the transmitter. The antennas were loaded vertical quarter-wave doublets which were connected to the receiver and transmitter respectively at their mid-points by short two-wire transmission lines. This equipment was driven along path 1 of Fig. 2, the distance between antennas being maintained constant long enough to make certain that there was no variation in the received field strength such as might be caused by the bottom of the lake if the water were not sufficiently deep. The distance between the transmitting and receiving antennas was measured by means of an auxiliary line. This consisted of a fish line for which the shrinkage due to becoming wet, or stretch

due to increased tension, was less than one per cent by experimental test. The distances at which measurements were made were laid off on this line when it was under a fixed tension. The same tension was applied to this line when making the measurements. The solid circles of Fig. 3 are a plot of the experimental data so obtained.

For distances greater than 150 meters it was necessary to change the experimental procedure slightly. The receiver was located at the end of a pier and the transmitter carried in the motorboat. The transmitter was driven over path 2 of Fig. 2. This method of procedure introduced difficulty in measuring the distances between transmitter and receiver. In an effort to reduce the error in measurement of distance, the distance was obtained by three independent methods. First, the motorboat was driven at a constant speed and a fixed direction across the lake between two points a known distance apart. Second, the distance was measured by a transit located on the receiving pier and a stadia rod erected on the motorboat. Third, the distance was measured by determining with a sextant the angle subtended at the boat by two poles erected on the shore, one at, and the other near the receiver. The angle between the line joining the two poles and the direction to the boat was also determined by means of the transit; the distance be-

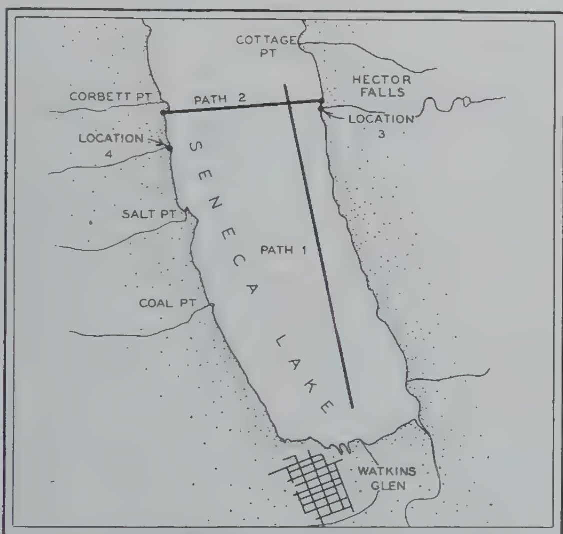

Fig. 2—Map of part of Seneca Lake showing the location of the experiment. Path 1 shows the location of the two-boat experiment, path 2 the one-boat experiment. Locations 3 and 4 indicate the positions of the terminals for the variable height test.

tween the poles was measured directly. For this part of the experiment a continuous record of the received field strength was obtained by means of a manually operated recorder attached to the receiver. The open circles shown in Fig. 3 represent a plot of the data so obtained.

The smooth curves were calculated by means of the following formulas, using values of ϵ and σ determined as follows: During the period of test the surface water temperature was 15.3 degrees centigrade which gives[13] $\epsilon=82.1$. The conductivity of five samples of water taken from various parts of the lake along which measurements were made was

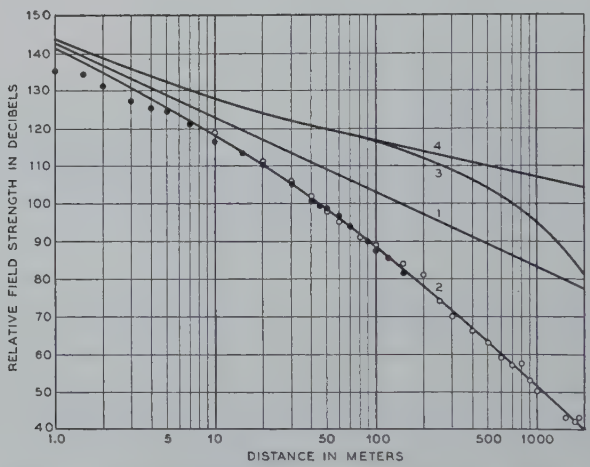

Fig. 3—Variation of received field strength with distance. Curve (1) is plot of equation (1) showing the inverse distance field that would result from propagation over plane earth of perfect conductivity. Curve (2) is a plot of equation (2) showing the variation of the received field strength according to Weyl and Norton. Curves (3) and (4) are plots of equation (3) showing the variation of the received field strength according to Sommerfeld and Rolf. Curves (2) and (3) are based on a dielectric constant of 82.1, a conductivity of 4.05×10^8 electrostatic units and a wave length of two meters. Curve (4) is for a perfect dielectric. The experimental points were obtained on a wave length of two meters with loaded quarter-wave doublets whose mid-points were 0.52 and 0.60 meter above the surface of the water. The solid circles represent measurements made with two boats and the open circles represent measurements made with one boat.

determined by L. A. Wooton of these Laboratories. The average value was found to be 4.988×10^8 electrostatic units with mean deviation of 0.006×10^8 at 1000 cycles and 25 degrees. Taking into account the effect of temperature on the conductivity[14] this gave $\sigma=4.05\times10^8$ electrostatic units.

[13] *See* International Critical Tables, vol. 6, p. 78; $\epsilon=80-0.4\ (T-20)$.

[14] Taking data from the International Critical Tables, vol. 6, pp. 233 and 234 the conductivity at 15.3 degrees would be 4.02 and 4.07 if the electrolyte were NaCl and KCl, respectively. A single measurement of the conductivity at 15 degrees centigrade $\pm\frac{1}{2}$ degree centigrade gave a conductivity of 3.96.

Curve (1) is a plot of the received field strength that would result from transmission over a plane earth of perfect conductivity:

$$E_0 = \frac{120\pi HI}{\lambda r}. \tag{1}$$

Curves 2 and 3 result from multiplying (1) by the magnitudes of

$$W = A - B/2 \approx C \tag{2}$$

and

$$S = A + B/2 \approx C + B \tag{3}$$

respectively, where,

$$A = 1 + \sum_{n=1}^{\infty} \frac{x^n e^{2in(\delta+\pi/4)}}{1\cdot 3\cdot 5\cdots(2n-1)} \tag{4}$$

$$B = \sqrt{2\pi x}\, e^{-(x/2)\sin 2\delta + i[(x/2)\cos 2\delta + \delta + \pi/4} \tag{5}$$

$$C = -\sum_{n=1} \frac{1\cdot 3\cdot 5\cdots(2n-1)}{x^n e^{2in(\delta-\pi/4)}} \tag{6}$$

$$xe^{2i\delta} = \frac{2\pi r/\lambda}{\epsilon - 2i\sigma/f}, \qquad 0 \leqq \delta \leqq \pi/4. \tag{7}$$

These follow from expressions given by Wise[15] when the magnitude of $\epsilon - 2i\sigma/f$ is large compared with unity.[16] $|W|$ is the attenuation factor corresponding to the formula derived by Weyl. $|S|$ is the attenuation factor as derived by Sommerfeld and used by him and by Rolf to calculate the variation of field strength with distance. B, the difference between S and W, corresponds to the surface wave component. For a perfect dielectric the exponent in B is a pure imaginary and curve (3) becomes curve (4).

The experimental points are in good agreement with curve 2 which is a plot of (2) and agrees with Weyl and Norton. At distances less than five meters ($2\frac{1}{2}$ wave lengths) the experimental points lie slightly below the theoretical curve and show a tendency towards oscillation. This is presumably due to the combined effect of the finite size of the antennas and their finite height above the water's surface. These oscillations may

[15] W. Howard Wise, "The grounded condenser antenna radiation formula," Proc. I.R.E., vol. 19, pp. 1684–1689; September, (1931).

[16] These expressions differ from those of Wise in that the sign of i has been changed so that the implied time factor is $e^{+i\omega t}$ in accordance with engineering practice instead of the $e^{-i\omega t}$ employed by Sommerfeld and Wise. Equation (4) is equivalent to Wise's expression (5). Equation (5) follows from the negative of Wise's (12) when it is remembered that changing the sign of i changes the Hankel function of the first kind into the corresponding one of the second kind and the Hankel function is replaced by the first term of its asymptotic expansion. Equation (6) is equivalent to Wise's expression (8).

be a vestige of the pronounced interference pattern that extends to greater distances with higher antennas. The discrepancy between the experimental points and curve 3 which is a plot of Sommerfeld's formula is so great that there can be no doubt as to the incorrectness of the latter.

Fig. 4—Picture of transmitting site at "4" of Fig. 2, showing portable 25-meter mast and transmitting antenna.

Variation of Field Strength with Height

To determine the variation of received field strength with antenna height, 25-meter portable masts were erected at locations 3 and 4 of Fig. 2. Fig. 4 shows a picture of the transmitting location at 4. Unfortunately it was impossible to get a location at the water's edge sufficiently removed from trees and the cliffs along the side of the lake to remove the possibility of their affecting to some extent the received

field strength. On vertical polarization the received field strength was determined as a function of the receiving antenna height for transmitting antenna heights of 24.8 and 2.5 meters (above the surface of the water). The measurements were repeated on horizontal polarization for the larger antenna heights. These experimental results are compared with theory in Fig. 5.

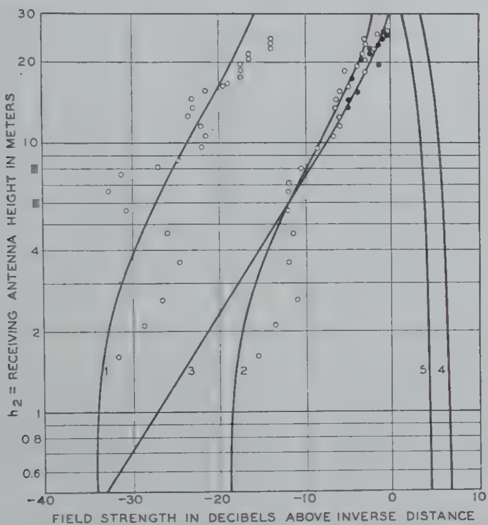

Fig. 5—Variation of received field strength with antenna height. Path length, 1800 meters. Curves (1) and (2) are plots of equation (9) for h_1 equal to 2.5 and 24.8 meters, respectively, which apply to vertical polarization if there is no surface wave. Curve (3) is a plot of equation (9) for $h_1 = 24.8$ meters which applies to horizontal polarization. Curves (4) and (5) are plots of the surface wave given by equation (8) for h_1 equal to 2.5 and 24.8 meters, respectively. The two sets of open circles represent experimental data taken on vertical polarization with h_1 equal to 2.5 and 24.8 meters, respectively. The solid circles represent experimental data taken on horizontal polarization with $h_1 = 24.8$ meters.

For the conditions of this part of the experiment B is large compared with C, so that $W \approx C$ and $S \approx B$. A more general expression for $|B|$ not limited to the surface of the earth, nor to large values of the complex index of refraction (but limited to $\epsilon \gg 2\sigma/f$) is:[17]

$$|B| = \frac{2\pi\epsilon^{9/4}}{(\epsilon+1)^{5/4}(\epsilon-1)} \sqrt{\frac{r}{\epsilon\lambda}}\, e^{-\frac{2\pi r}{\lambda}\frac{\sigma/f}{\sqrt{\epsilon(\epsilon+1)^3}} - \frac{2\pi(h_1+h_2)}{\lambda}\frac{\sigma/f}{(\epsilon+1)^{3/2}}}. \tag{8}$$

In a companion paper[18] it is shown that if there is no surface wave the attenuation factor is to a first approximation

[17] For the conditions of the experiment the error introduced by the approximations of (8), (9), (10), and (11) is entirely negligible.

[18] Charles R. Burrows, "Radio propagation over plane earth—Field strength curves," *Bell Sys. Tech. Jour.*, vol. 16, pp. 45–75; January, (1937).

$$\frac{E}{E_0} = \frac{1}{2}\left| 1 + \left(R + \frac{(R+1)^2\lambda r}{2\pi i(h_1+h_2)^2}\right)e^{-4\pi h_1 h_2/\lambda r}\right| \tag{9}$$

where R is the appropriate coefficient of reflection.[19] The smooth curves of Fig. 5 are plots of this expression for the conditions of the experiment.

Sommerfeld[20] has shown that a horizontal electric antenna does not generate a surface wave in the direction perpendicular to the axis of the antenna. Hence there is no uncertainty as to the correct expression for the field in the case of horizontal antennas. This, together with the fact that at the greater heights the antennas may be considered to be in free space as far as their impedance is concerned, allows the measurements with horizontal polarization to be taken as a calibration of the measuring equipment. Using this calibration the received field strength is found to be −31.5 decibels above the inverse distance field with antenna heights of 2.5 and 1:6 meters. For antennas on the ground Weyl's formula gives a value of −36.8 decibels while that of Sommerfeld gives value of +6.6 decibels. Hence the absolute value of the received field strength is in agreement with Weyl.

These experimental results are compared with theory in Fig. 5. The measured value of field strength actually decreases with decrease in antenna height whereas Sommerfeld's formula predicts an increase as shown by curves (4) and (5). The oscillations in the experimental curves are presumably due to reflections from the cliffs and trees behind the receiving antenna. While the agreement between the experimental and theoretical curves is not all that could be desired, it is the best that could be expected under the conditions of the experiment and in no way introduces any doubt as to the error in the Sommerfeld curves which predict a field strength about 100 times that measured.

[19] When $\epsilon \gg 2\sigma/f$, $R=-k$ and if in addition h_1+h_2 is small $(1-k)=\frac{2\epsilon}{\sqrt{\epsilon-1}}\frac{h_1+h_2}{d}$ for vertical polarization and $(1-k)=\frac{2}{\sqrt{\epsilon-1}}\frac{h_1+h_2}{d}$ for horizontal polarization. Under these conditions (9) reduces to

$$|C| = \frac{\epsilon^2}{(\epsilon-1)(2\pi r/\lambda)}\sqrt{\left[1+\frac{\epsilon-1}{\epsilon^2}\left(\frac{2\pi h_1}{\lambda}\right)^2\right]\left[1+\frac{\epsilon-1}{\epsilon^2}\left(\frac{2\pi h_2}{\lambda}\right)^2\right]} \tag{10}$$

for vertical polarization and to

$$|D| \quad \frac{2\pi h_1 h_2}{\lambda r}\sqrt{\left[1+\frac{1}{\epsilon-1}\left(\frac{\lambda}{2\pi h_2}\right)^2\right]\left[1+\frac{1}{\epsilon-1}\left(\frac{\lambda}{2\pi h_2}\right)^2\right]} \tag{11}$$

for horizontal polarization. The coefficient of the radical in (10) gives the value of $|C|$ on the ground.

[20] Arnold Sommerfeld, "Über die Ausbreitung der Wellen in der drahtlosen Telegraphie, *Ann. der Phys.*, ser. 4, vol. 81, pp. 1135–1153; December 11, (1926).

Conclusions

These experiments on the propagation of two-meter waves over Seneca Lake have shown that the surface wave component of Sommerfield is not set up by simple antennas on the surface of the earth. Measurements were made on the variations of the field strength with distance, under conditions for which this component, if present, would have been large compared with all the other components. They agreed with the curves calculated by neglecting this component. Measurements made on the variation of the received field strength with antenna height under similar conditions showed that the received field strength increased with antenna height, whereas Sommerfeld's surface wave would have decreased. Finally the absolute value of the received field strength was found to be less than that predicted by Sommerfeld by a factor of about a hundred. Accordingly the Sommerfeld-Rolf curves are in error for all conditions for which the dielectric constant cannot be neglected.

As a result of this fact it follows that the asymptotic series development of the received field strength is a true asymptotic expansion and does not require the addition of an exponential term. Hence the series development of the problem by Strutt[21] and Wise[22,23] may be used with confidence.

Acknowledgment

The writer wishes to acknowledge the co-operation of his associates Messrs. Loyd E. Hunt and Alfred Decino in performing the experiment. He also wishes to thank Dr. W. Howard Wise who has kindly checked the derivations and mathematical statements made in this paper.

[21] M. J. O. Strutt, "Strahlung von Antennen unter dem Einfluss der Erdbodeneigenschaften; (a) elektrische Antennen, (b) magnetische Antennen, (c) Rechnung in zweiter Näherung, (d) Strahlungsmessungen mit Antennen," *Ann. der Phys.*, ser. 5, vol. 1, pp. 721–772; vol. 4, pp. 1–16; vol. 9, pp. 67–91; (1929–1931).

[22] W. Howard Wise, "Note on dipole radiation theory," *Physics*, vol. 4, pp. 354–358; October, (1933).

[23] W. Howard Wise, "Asymptotic dipole radiation formulas," *Bell Sys. Tech. Jour.*, vol. 8, pp. 662–671; October, (1929).

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TWO-MESH TUNED COUPLED CIRCUIT FILTERS*

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Summary—*Tuned coupled circuits have been the subject of many investigations, but few of these have produced results which are useful to the design engineer. A direct attack, avoiding the special terminology and procedures of general filter theory, seems the most effective. Several such attacks have been made, but either the results have not been fully developed, or serious restrictions have been placed upon the circuits. One common restriction is that the circuits are identical; another, that they are coupled by a pure reactance. These limitations made the resulting theory inapplicable to the study of such important matters as detuning, unequal circuit resistances, resistance in the coupling impedance, etc.*

In this paper, a reasonably simple analysis is developed which is free from the foregoing objections. The results include and collect into a correlated whole many relations which have been derived before, as well as a number of new ones.

Circuits which are tuned alike and coupled by a pure reactance are treated first. Universal resonance curves are developed which make it possible to determine rapidly the characteristics of any pair of isochronous circuits, once their constants are known. Formulas are derived for band width at any given number of decibels down, ratio of height of peaks to valley, etc. It is shown that the concept of critical coupling is inadequate when the circuit resistances are unequal, and a new quantity, transitional coupling, is introduced. Methods for the design of a tunable filter of constant band width are developed. The shift of the peaks with changes in coupling reactance is considered. The form of the primary current and the impedance across the primary are also treated.

Next, the case of circuits tuned to slightly different frequencies is considered. A general expression for the secondary current is derived, and it is shown that detuning will give an unsymmetrical resonance curve when, and only when, the circuit resistances are unequal. It is shown that when the resistances are equal, the universal resonance curves of the preceding section can be applied to the case of detuned circuits. And it is further pointed out how the formulas may be applied to the study of stagger tuned circuits.

Finally, the case of coupling by a complex impedance is considered. It is shown how this will produce a dissymetry in the resonance curve, unless the coupling is very small. And it is demonstrated how the universal resonance curves may be used for computing the response of two circuits coupled by an impedance having a loss that is reasonably small but not negligible. Typical effects of resistance in the coupling impedance are illustrated.

THE WIDE use of tuned coupled circuits in communication systems, and particularly in radio receivers, has made these elements of considerable importance. A pair of tuned coupled circuits ordinarily constitutes a band-pass filter, but, because such a filter contains only two meshes and because it cannot be satisfactorily

* Decimal classification: R386. Original manuscript received by the Institute, October 19, 1936.

treated without taking into account resistances, the conventional filter theory, using the concepts of characteristic impedance and propagation constant, is not particularly convenient in analyzing its performance. Useful results are more easily arrived at by treating a coupled pair with a perfectly straightforward attack based on ordinary Kirchhoff's laws, without any resort to the special viewpoints or terminology of general filter theory.

There have been many such direct attacks, and they have resulted in a considerable mass of information about the behavior of coupled circuits. However, there seems to be in the literature no really extensive description of their characteristics and peculiarities suitable to the needs of the design enginer. Many of the analyses have been made under restrictions which limit the usefulness of the results. One common restriction is that the circuits are identical, another that they are coupled by a pure reactance. These limitations make the resulting theory inapplicable to the study of such important matters as detuning, unequal circuit resistances, resistance in the coupling impedance, etc. In many phases of practical work these phenomena occur frequently and a mathematical description is very desirable.

On the other hand, in those cases where no restrictions have been placed on the analysis, the results have often been extremely complicated, or incompletely developed, or have been in a form which was of little use to the practical engineer.

In the present paper, an attempt is made to develop a reasonably simple analysis free from the foregoing objections. Great complexity is avoided by the use of suitable approximations, which, however, introduce only small errors. The results include, and collect into a correlated whole suitable for application to practical problems, many relations which have been derived before, as well as a number of new ones.

We shall deal specifically with the type of filter having a passed band the width of which is only a few per cent of the center frequency, the analysis being inapplicable to very wide band filters such as are used for passing the whole broadcast band at once. The circuits of the former must have a reasonably high Q, of about 20 or usually much more. Only the steady-state solutions will be considered.

The analysis will be developed on the basis of the electromotive force in series with one of the tuned circuits. However, it will be pointed out that any arrangement of the driving electromotive force can be reduced to an equivalent series electromotive force at any given frequency. We shall assume that the character of the circuits associated with the coupled pair is such that the equivalent series electromotive force will not vary appreciably in magnitude over the small frequency

range in which we are interested. This means that the associated circuits must have no resonant frequencies near the center frequency of the coupled circuit filter. It will also be necessary to assume that the value of the coupling impedance between the two circuits does not change by any important amount over the frequency range we are studying.

The introduction of approximations and of special symbols is necessary to avoid tedious complexity. It is realized that special symbols are always an annoyance, but the number here involved is relatively small and their physical significance is reasonably evident. It is hoped that the relations which are developed are sufficiently compact and complete to be of real practical use.

The general method of procedure is identical with that used by Beatty,[1] but is carried much further, since his analysis was restricted to the case of identical circuits coupled by a pure reactance.

No discussion is given of the power relations in tuned coupled circuits. It is hoped to make such relations the subject of a later paper.

No examination of the effects of regeneration is made, since it can occur in so many different ways that any general analysis would be apt to become very unwieldy. In most cases we wish to have as little feedback as possible in a band-pass filter system. Proper care in the placing and shielding of circuit elements can often reduce it to a point where it is no longer appreciable. Perhaps one of the most troublesome forms of feedback is due to the residual capacitance between the grid and plate of a screen-grid tube. That this may have serious effects is shown in the series of articles by Cocking.[2] However, if the filter works into a frequency converter or into a detector, these effects are absent. When two filter amplifier stages are cascaded on the same frequency, trouble may be encountered, but in many practical cases it is unimportant. In any event, it can, if necessary, be eliminated by neutralization.

PART I

Reduction of Various Circuits to a Common Form

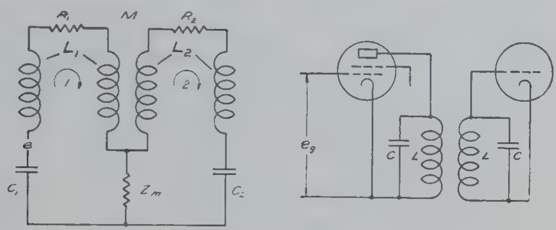
There are various ways in which narrow band tuned coupled circuits are used in communication equipment. It will therefore be convenient to reduce the circuits which occur in practice to a simple equivalent circuit which can be readily solved. This is easily done by

[1] R. T. Beatty, "Two-element band-pass filters," *Wireless Eng.*, vol. 9, pp. 546–557; October, (1932).

[2] W. T. Cocking, "Variable selectivity and the I. F. amplifier," *Wireless Eng.*, March, April, and May, (1936).

the use of Thevenin's theorem, since in any actual case we have a driving voltage coupled to a simple tuned pair by a more or less complex intermediate network.

Fig. 1 (a) shows a pair of circuits coupled by the mutual inductance M and the common impedance Z_m. In the simplest case these circuits would be driven by an electromotive force of zero internal impedance connected in series with the primary circuit. In practice, however, the primary is coupled by some means to a driver, which may be the plate-cathode path of a vacuum tube, the voltage induced in an antenna, etc.



(a) (b)

Fig. 1(a)—Simple coupled pair, with the driving voltage in series with the primary.
1(b)—Screen-grid amplifier with band-pass filter.

In any given case, if the primary is opened at a convenient point we may look back toward the driver and see a certain effective electromotive force having a certain effective internal impedance. These two quantities will be very nearly constant over the small percentage frequency range in which we are interested, and hence we may consider the driver and its connecting network to be replaced by a simple generator in series with the primary circuit. It will therefore suffice to analyze the circuit of Fig. 1(a), since the results of such an analysis can be applied to an actual circuit merely by computing the particular relation between the actual driving electromotive force and the equivalent electromotive force acting in series with the primary, and then by computing the impedance reflected into the primary by the driver and its coupling network.

As a simple example of the foregoing, consider the system of Fig. 1(b). The driving voltage is μe_g and the internal impedance of the driver is r_p. Application of Thevenin's theorem shows that Fig. 1(b) can be reduced to Fig. 1(a) by setting

$$e = \frac{\mu e_g(1/j\omega C)}{r_p + 1/j\omega C} \tag{1}$$

and adding to the actual series impedance of the tuned circuit the quantity

$$\frac{r_p/j\omega C}{r_p + 1/j\omega C}. \tag{2}$$

In most cases r_p will be very large as compared with $1/\omega C$. Hence, if we are not interested in the exact phase relation between μe_g and e, we may simplify (1) to

$$e = \frac{\mu e_g}{r_p} \frac{1}{\omega C} = \frac{g_m e_g}{\omega C}. \tag{3}$$

We must, however, be careful in reducing (2). If we neglect $1/j\omega C$ in the denominator, then (2) becomes merely $1/j\omega C$, and there would be no impedance reflected into the tuned circuit from the plate of the tube. We know from experience that this is not the case. Hence, rejection of $1/j\omega C$ in the denominator is not justified.

In order to get the proper result, first rationalize (2), giving

$$\frac{r_p/\omega^2 C^2 - jr_p^2/\omega C}{1/\omega^2 C^2 + r_p^2}. \tag{4}$$

We may now safely neglect $1/\omega^2 C^2$ in the denominator in comparison with r_p^2. Equation (4) thus reduces to

$$\frac{1}{\omega^2 C^2 r_p} - \frac{j}{\omega C}. \tag{5}$$

The first term represents the resistance effectively introduced into the tuned primary by the plate resistance of the tube. Although small, it is important, since it may be a considerable fraction of the true resistance of the tuned circuit. This effect will change the performance of the coupled circuits more than a slight change in the magnitude of the equivalent series voltage e and explains why $1/j\omega C$ may be safely neglected with respect to r_p in (1) but not in (2).

To complete the reduction of Fig. 1(b) to 1(a), we have merely to set $Z_m = 0$, and to apply (3) and (5).

Before proceeding to the treatment of Fig. 1(a), let us note the effect of a small capacitance between the high potential ends of the tuned circuits.

Effect of Small Capacitance Between High Potential Sides of Tuned Circuits

In many cases, a small capacitance C_h may exist between the high potential sides of the tuned circuits. Fig. 1(a) is then replaced by Fig. 2(a), in which the arrangement of the elements has been changed so as to emphasize the Δ connection of the three capacitances. It is well

known that any Δ circuit may be replaced by an equivalent T network. The relations between the impedances of the elements of equivalent Δ and T networks are given by Johnson.[3] If we make the simplifying assumption that C_h is quite small, so that

$$X_{C_h} \gg X_{C_1} + X_{C_2} \tag{6}$$

then Johnson's formulas show that the equivalent T is made up of three condensers having values as follows:

$$C_a = C_1, \qquad C_b = C_2, \qquad C_s = C_1C_2/C_h. \tag{7}$$

This T network is shown in Fig. 2(b), and it is evident that the capacitance C_h across the high potential sides of the circuits can be replaced by a condenser C_s in series with Z_m'.

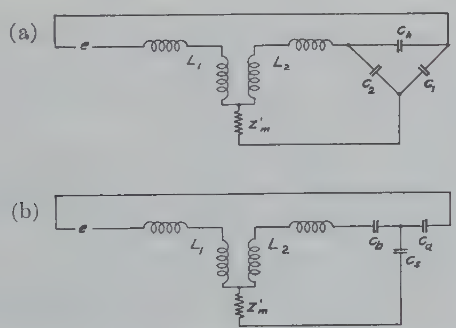


Fig. 2(a)—Coupled pair with capacitance between the high potential sides of the windings.
2(b)—Circuit equivalent to that of (a), but with Δ connection of capacitances replaced by a T.

If the high side capacitance has a phase impurity, due to losses of some sort, then instead of the simple capacitance C_s in series with Z_m' we shall have a complex impedance. If the impedance between the high potential sides is $Z_h = R_h - (j/\omega C_h)$ then Johnson's relations show that the equivalent impedance that must be placed in series with Z_m' is

$$Z_s = \frac{-R_h - j/\omega C_h}{\omega^2 C_1 C_2 (R_h^2 + 1/\omega^2 C_h^2)}. \tag{7a}$$

It is surprising to note that the real part of this expression is negative. Of course, this fictitious equivalent negative resistance can never produce any amplifier effects. What it does do is to produce a dissymmetry in the resonance curve of the opposite sort from that produced

[3] K. S. Johnson, "Transmission Circuits for Telephonic Communication," p. 282.

by a true positive resistance in Z_m.[4] This will be evident from a study of Part IV.

Z_m as used in this paper will include Z_s and hence the effects of Z_h will not have to be separately considered.

Solution of Equations

Referring to Fig. 1(a), let,

L_1 = total self-inductance of primary circuit, including the effective series inductance of Z_m and any inductance reflected from the driver circuit

C_1 = total effective series capacitance of the primary circuit including Z_m, etc.

R_1 = total effective series resistance of the primary circuit including Z_m, etc.

L_2 = total self-inductance of the secondary circuit including Z_m

C_2 = total effective series capacitance of the secondary circuit including Z_m and any capacitance added by a load across the tuning condenser

R_2 = total effective series resistance of secondary circuit including Z_m and any equivalent series resistance caused by a load across the tuning condenser

X_m = total impedance common to primary and secondary circuits

M = mutual inductance between primary and secondary circuits

$Z_1 = \mathrm{R}_1 + j\omega L_1 - j/\omega C_1 + Z_m$

$Z_2 = \mathrm{R}_2 + j\omega L_2 - j/\omega C_2 + Z_m$

$Z_{12} = Z_m \pm jM\omega$ = total effective coupling impedance

$Z_{12} = r + ju.$

Any capacitance that may exist between the high potential sides of the two circuits is to be replaced by an equivalent component of Z_m, as already discussed.

The equations of Fig. 1(a) are

$$Z_1 i_1 - Z_{12} i_2 = e \tag{8}$$

$$Z_2 i_2 - Z_{12} i_1 = 0, \tag{9}$$

the solutions of which are

$$i_1 = \frac{Z_2 e}{Z_1 Z_2 - Z_{12}^2} \tag{10}$$

$$i_2 = \frac{Z_{12} e}{Z_1 Z_2 - Z_{12}^2}. \tag{11}$$

[4] That this might be the case was suggested to the writer by Mr. Kelly Johnson of the Wells-Gardener Company of Chicago.

We shall have occasion to consider the effects of dissimilar tuning of the circuits and of resistance in the coupling impedance. However, both of these circuit conditions can be more readily treated after we have developed in detail the solutions for the case of $X_1 = X_2 = X$ and $Z_{12} = 0 + ju$, a pure reactance.

PART II

Case of Isochronous Circuits Coupled by a Pure Reactance

Since we are dealing with a small percentage frequency range, it will be permissible to regard u as constant over this range. Let u_0 be the value of u at the resonant frequency of either circuit taken alone. Then $Z_{12} = ju_0$ and (11) becomes

$$i_2 = \frac{ju_0 e}{Z_1 Z_2 + u_0^2}. \tag{12}$$

Rationalizing, and remembering that $X_1 = X_2 = X$, we get

$$|i_2| = \frac{u_0 e/\sqrt{R_1 R_2}}{\sqrt{R_1 R_2}\sqrt{\left(1 + \frac{u_0^2}{R_1 R_2} - \frac{X^2}{R_1 R_2}\right)^2 + \frac{X^2}{R_1 R_2}\left(\sqrt{\frac{R_1}{R_2}} + \sqrt{\frac{R_2}{R_1}}\right)^2}}. \tag{13}$$

It will now be convenient to introduce a few abbreviations which will be useful throughout the analysis. Let

$$s = \frac{u_0}{\sqrt{R_1 R_2}} \tag{14}$$

$$b = \frac{R_1}{R_2} + \frac{R_2}{R_1} = \frac{R_1^2 + R_2^2}{R_1 R_2} \tag{15}$$

$$v = \frac{X}{\sqrt{R_1 R_2}}. \tag{16}$$

s is an effective measure of the tightness of coupling, and, since the term "coefficient of coupling" is commonly given another meaning, we shall call s the index of coupling.

Inserting these abbreviations, (13) becomes

$$|i_2| = \frac{se}{\sqrt{R_1 R_2}\sqrt{(1 + s^2)^2 - 2v^2(s^2 - b/2) + v^4}}. \tag{17}$$

The factor of proportionality $e/\sqrt{R_2 R_1}$ is of no use in studying the shape and general characteristics of the resonance curves. Let us, therefore, get rid of it by introducing another abbreviation:

$$y_2 = 2\sqrt{R_1R_2}\,|\,i_2\,|/e. \tag{18}$$

Then,

$$y_2 = \frac{2s}{\sqrt{(1+s^2)^2 - 2v^2(s^2 - b/2) + v^4}}. \tag{19}$$

Equation (18) has been set up so that when the impressed frequency is equal to the resonant frequency of the circuits ($v=0$), y_2 will be unity for critical coupling ($s=1$).

Equation (19) completely determines the form of the resonance curve, and we shall see that it is a very useful expression. s is a measure of the degree of coupling and b depends solely on the ratio of the circuit resistances; v is proportional to the reactance of either circuit, which reactance is proportional, over the range of interest, to the frequency departure from resonance. Thus

$$X = \omega L - 1/\omega C,$$

L and C being the total constants for either circuit. Let $\omega_0/2\pi$ be the resonant frequency and

$$\begin{aligned}
\omega &= \omega_0 + \Delta\omega \\
X &= \omega_0 L + \Delta\omega L - 1/(\omega_0 + \Delta\omega)C \\
&= \omega_0 L + \Delta\omega L - \frac{1}{\omega_0 C} + \frac{\Delta\omega}{\omega_0^2 C} \qquad (20) \\
&= \left(\omega_0 L + \frac{1}{\omega_0 C}\right)\frac{\Delta\omega}{\omega_0} = 2\omega_0 L \cdot \frac{\Delta f}{f_0}.
\end{aligned}$$

If we denote by X_{L0} the magnitude of the reactance of the coil alone, or the condenser alone, at the resonant frequency, then

$$X = 2X_{L0}\frac{\Delta f}{f_0} \tag{21}$$

$$v = \frac{2X_{L0}}{\sqrt{R_1R_2}} \cdot \frac{\Delta f}{f_0} = \frac{4\pi L}{\sqrt{R_1R_2}}\Delta f. \tag{22}$$

v is evidently proportional to Δf, and changes sign on going through resonance.

It will be noted that (19) contains only even powers of v, and hence the curve of y_2 vs. v, or of y_2 vs. Δf, is symmetrical about the resonant frequency. For large values of Δf, the simple relation expressed by (22) would no longer hold and the resonance curve would depart from symmetry.

Universal Resonance Curves

From (19) may be plotted universal resonance curves which allow the rapid calculation of the frequency characteristics of pairs of isochronous circuits for four different values of R_1/R_2 (or R_2/R_1). Curves of this sort have been developed by Beatty[1] for the case of identical

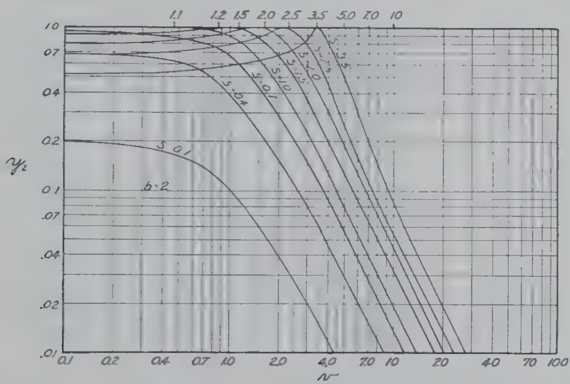


Fig. 3—Universal resonance curves for the case of equal circuit resistances.

circuits, which require only a single family. In Figs. 3, 4, 5, and 6 are shown families of curves for $b=2$, 10, 50, and 200, respectively, corresponding to values of R_1/R_2 (or R_2/R_1) of 1, 9.919, 49.98, and 200, very closely. The curves of Fig. 3 are identical with those of Beatty.

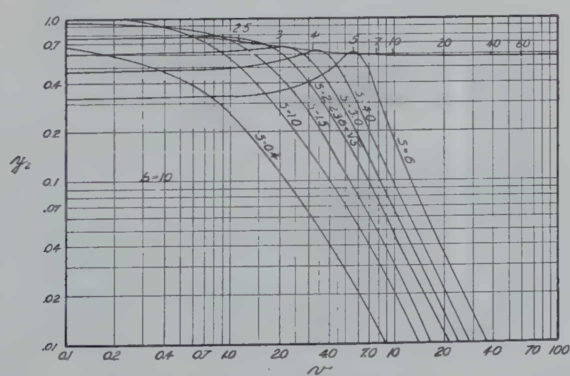


Fig. 4—Universal resonance curves for a circuit resistance ratio of 9.19:1.

When one of these families of curves is plotted on a convenient sized sheet of log paper, the curve of secondary current vs. frequency can be readily drawn for a given pair of circuits. The family corresponding to the value of R_1/R_2 to be used is chosen, and the value of $L/\sqrt{R_1R_2}$ is computed. Then the value of v at one kilocycle off tune

is determined by (22), setting $\Delta f = 1.0$. A piece of the same graph paper is placed over the family of curves with the horizontal edges of the two sheets coinciding. The sheets are then laid on a glass plate having a light behind it, and the blank one moved in a horizontal direction until the unity abscissa of the blank sheet lies directly over the value of v

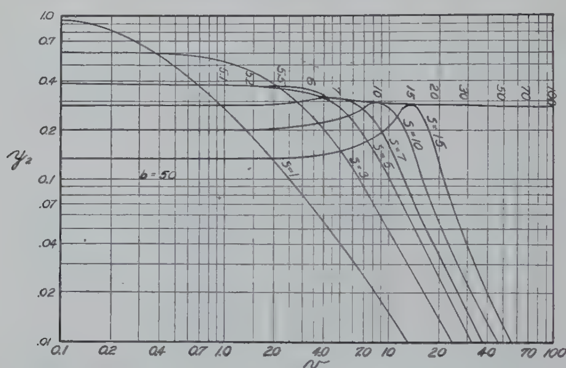


Fig. 5—Universal resonance curves for a circuit resistance ratio of 49.98:1.

computed for one kilocycle, this value being read on the sheet containing the family of curves. The curve for the desired value of s is then traced on the upper sheet. The abscissa of this sheet now reads directly in kilocycles, and the desired resonance curve is obtained.

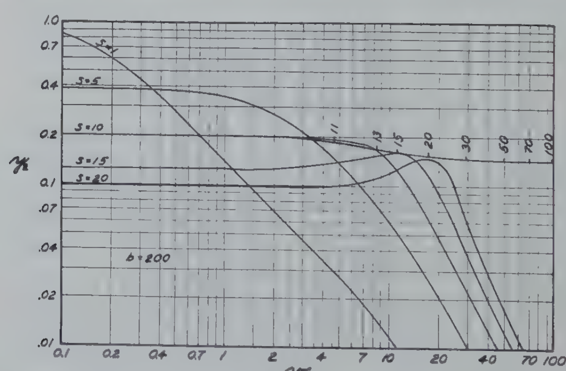


Fig. 6—Universal resonance curves for a circuit resistance ratio of 200:1.

The gently sloping curve near the top of Fig. 4 shows the locus of the peaks of the resonance curves as s is varied over the range of values indicated by the appended numerals. Similar curves are shown in Figs. 5 and 6. In Fig. 3 the curve is horizontal, and the scale of s is shown along the top edge of the figure.

These four figures show interesting changes that take place in the resonance curves as R_1/R_2 is varied. When $R_1=R_2$, all curves for couplings greater than unity have the same maximum value of unity, but when the resistances are unequal the peaks become lower as s is increased above unity. Were the two circuits to be retuned for maximum secondary current, it would be possible to raise y_2 to unity, but the resonance curve (y_2 vs. v) would no longer be symmetrical and would have one peak less than unity. This lack of symmetry resulting from the combination of conditions $R_1 \neq R_2$ and circuits tuned to different frequencies will be discussed later.

In Fig. 7 are shown two pairs of curves, the components of each pair being of similar shape but having different values of b. It will be

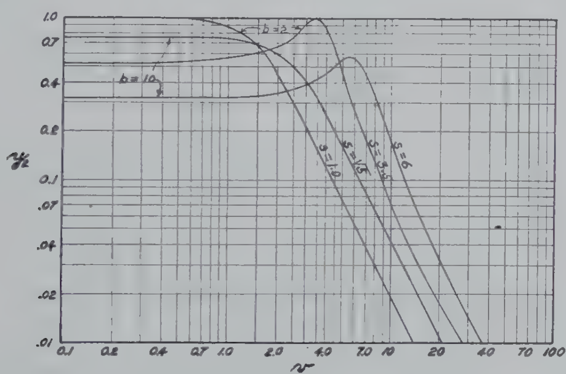


Fig. 7—Comparisons of curves having different values of s and b.

noted that the two peaked curves are very nearly the same shape and could be brought into substantial coincidence by applying appropriate multiplying factors to both ordinates and abscissas of one of them. This fact shows that, for a given ratio of peak to valley of the curve, the selectivity, from the peak out is not greatly affected by changes in b (i.e., R_1/R_2). This is not obvious from a cursory comparison of Figs. 3 and 4.

The other pair of curves shows the contrast due to different values of b, with transitional coupling in each case.

Under some circumstances still more families of resonance curves, for other values of R_1/R_2, might be required. A large set of sheets could readily be computed from (19), but in many cases the approximate shape of a resonance curve can be sketched from certain simple relations which we shall proceed to develop.

Width Between Peaks

To obtain the value of v which makes y_2 a maximum, we differentiate (19) with respect to v and equate the derivative to zero. The result of this process is

$$v = 0$$

or,

$$v_m = \pm \sqrt{s^2 - b/2}. \tag{23}$$

From the shape of the resonance curves, it is evident that $v=0$ gives a peak for loose coupling and a minimum (valley) for tight coupling.

Equation (23) can be valid only if $s^2 \geqq b/2$. When $s^2 \geqq b/2$, there are two peaks; when $s^2 \leqq b/2$, there is only one peak. The band width between peaks is proportional to $2v_m$.

$$v_m = \frac{4\pi L}{\sqrt{R_1 R_2}} (\Delta f)_m$$

$$(\Delta f)_m = \pm \frac{\sqrt{R_1 R_2}}{4\pi L} \sqrt{s^2 - \frac{b}{2}} = \frac{\sqrt{R_1 R_2}}{4\pi L} \sqrt{\frac{u_0^2}{R_1 R_2} - \frac{R_1^2 + R_2^2}{2R_1 R_2}}.$$

The band width between peaks is

$$(BW)_p = 2(\Delta f)_m = \frac{1}{2\pi L} \sqrt{u_0^2 - \frac{(R_1^2 + R_2^2)}{2}}. \tag{24}$$

When $R_1 = R_2 = R$ and $u_0 = M\omega_0$, this reduces to the familiar

$$(BW)_p = 1/2\pi L \sqrt{M^2 \omega_0^2 - R^2}. \tag{25}$$

Height of Resonance Curve at Center

When $v=0$, (19) becomes

$$y_{20} = 2s/(1 + s^2). \tag{26}$$

This relation is independent of b, and hence of R_1/R_2. A plot of (26) is shown in Fig. 8.

Width of Curve at Height Equal to Height at Center

To obtain this width, we eliminate y_2 between (19) and (26), and solve for v. The result is

$$v_1 = \sqrt{2(s^2 - b/2)}. \tag{27}$$

From (23) and (27) it appears that

$$v_1 = v_m \sqrt{2}, \tag{28}$$

or, the width of the curve at a height equal to that at the center is $\sqrt{2}$ times as great as the width between the peaks, a result already obtained by Oatley.[5]

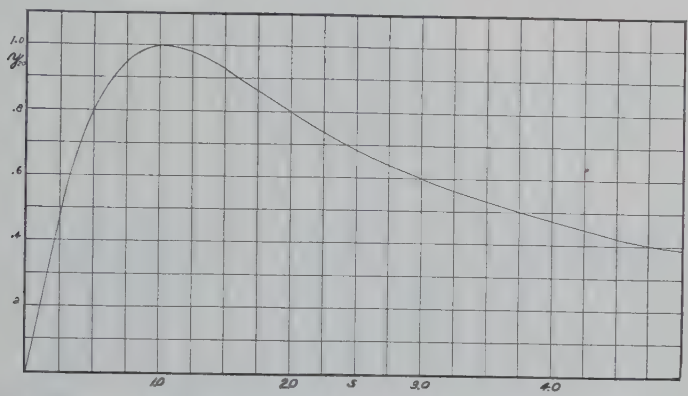


Fig. 8—Gain at the center of the band as a function of coupling index.

Height of Peaks

Putting (23) into (19) gives

$$y_{2m} = \frac{2s}{\sqrt{(1+s^2)^2 - (s^2 - b/2)^2}} \tag{29}$$

$$= \frac{2s}{\sqrt{1 + s^2(2+b) - b^2/4}}. \tag{30}$$

The peak envelope curves of Figs. 4, 5, and 6 have been plotted by eliminating s between (30) and (23) and plotting y_{2m} vs. v_m.

The relations (23), (26), (28), and (30) give the principal features of the resonance curve. When we add the fact that for large values of v, y_2 is given by

$$y_2 = 2s/v^2 \tag{31}$$

we have available the information necessary to sketch in a resonance curve for any value of b.

Ratio of Peak to Valley

The ratio of the height of the peaks to the height of the valley is of interest, since it determines the frequency distortion inside the passed band of the filter. This ratio is obtained by dividing (29) or (30) by (26), which gives

[5] C. W. Oatley, "The theory of band-pass filters for radio receivers," *Wireless Eng.*, vol. 9, pp. 608–614; November, (1932).

$$\frac{y_{2m}}{y_{20}} = \frac{1 + s^2}{\sqrt{(1 + s^2)^2 - (s^2 - b/2)^2}} \tag{32}$$

$$= \frac{1 + s^2}{\sqrt{1 + s^2(b + 2) - b^2/4}}. \tag{33}$$

Plots of (33) for four values of b are shown in Fig. 9.

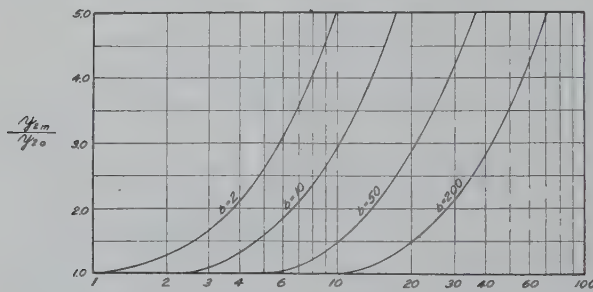


Fig. 9—Ratio of peak to valley as a function of coupling index for various values of the ratio of circuit resistances.

Critical Coupling and Transitional Coupling

It has often been stated, explicitly or implicitly, that the resonance curve of a pair of isochronous coupled circuits shows a single peak when $s \leqq 1.0$, but shows two peaks when $s > 1.0$.

Now, from the analysis which has been developed, it is evident that when $R_1 \neq R_2$ two peaks will be developed only when $s^2 > b/2$, and there will be only one peak in the range $b/2 \geqq s > 1.0$. This is evident in Figs. 4, 5, and 6. Hence the transition from one to two peaks occurs at[6]

$$s = \sqrt{b/2} = \sqrt{\frac{R_1^2 + R_2^2}{2R_1R_2}} \tag{34}$$

and the name "transitional coupling" is therefore suggested for this value of the coupling index.

Equation (34) can also be written

$$u_0 = \sqrt{\frac{R_1^2 + R_2^2}{2}} \tag{35}$$

which shows that at transitional coupling the total coupling reactance is equal to the root-mean-square of the total resistances of the primary and secondary circuits.

[6] The same equation in different notation is contained in a paper by E. S. Purington, "Single and coupled circuit systems," Proc. I.R.E., vol. 18, pp. 983–1016; June, (1930).

Even when the circuit resistances are unequal, the concept of critical coupling ($s=1.0$) is a useful one, since it is the value of coupling index that gives maximum secondary current at the center of the resonance curve, regardless of the value of R_1/R_2. Moreover, that maximum current is

$$y_{2m} = 1.0 \tag{36}$$

or,

$$i_{2m} = \frac{e}{2\sqrt{R_1R_2}}. \tag{37}$$

Both transitional and critical coupling are useful quantities in the case of isochronous circuits having unequal resistance. When the resistances are equal, the two quantities become the same.

Band Width a Given Number of Decibels Down

The value of v at which the resonance curve is a given number of decibels down from its value at the center, for a given value of b and s, is of interest, since the band width at reduced response is often required. The inverse relation, in which s is expressed as a function of b and v, is also useful, since, with a given pair of coils, the value of s required for a certain band width any specified number of decibels down, can be calculated.

The ratio of response at any point on the curve to the response at the center is obtained by dividing (19) by (26). The result is

$$\frac{y_2}{y_{20}} = \frac{1 + s^2}{\sqrt{(1 + s^2)^2 - 2v^2(s^2 - b/2) + v^4}}. \tag{38}$$

Solving this for v^2, we get

$$v^2 = \left(s^2 - \frac{b}{2}\right)\left[1 \pm \sqrt{1 + \frac{(1 + s^2)^2}{\left(s^2 - \dfrac{b}{2}\right)^2}\left(\frac{y_{20}{}^2}{y_2{}^2} - 1\right)}\,\right]. \tag{39}$$

The plus sign is chosen to give values of v outside of the peaks. The minus sign will give values of v inside the peaks, but only for the limited range of y_{20}/y_2 lying between valley and peaks will a real answer (v^2 positive) be obtained.

With a given s and b, the band corresponding to any value of y_{20}/y_2 can be readily obtained with the help of (39). Let us now solve (38) for s in order to obtain an expression which will enable us to choose the proper coupling coefficient to give a specified band width when b and y_{20}/y_2 are given.

Let,

$$F = \left(\frac{y_{20}}{y_2}\right)^2 - 1. \tag{40}$$

Solving (39) for s^2 we get

$$s^2 = -\left(1 + \frac{v^2}{F}\right) \pm v\sqrt{\frac{2 + b + 2v^2}{F} + \frac{v^2}{F^2}}. \tag{41}$$

This is a fairly simple equation from which s can be readily calculated.

A case of particular interest is that of response three decibels down from the center of the curve. Then $(y_{20}/y_2)^2 = 2$, or $F = 1.0$, and (41) becomes

$$s^2 = -(1 + v^2) + v\sqrt{2 + b + 2v^2}. \tag{42}$$

Plots of s vs. v for $b=2$ and $b=10$ are shown in Fig. 10. These curves

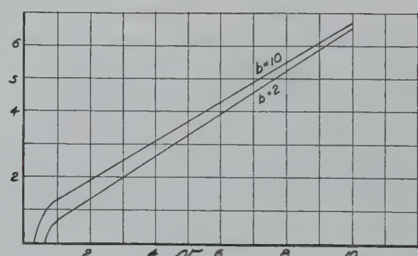


Fig. 10—Plots of coupling index which will give a response three decibels down from the center of the resonance curve for the values of v shown in the abscissa.

give the value of s for any specified band width at three decibels down from the center of the curve, but tell nothing about how peaked the resulting resonance curves will be. This last information can be obtained from Fig. 9.

Tunable Filter of Approximately Constant Band Width

In a tuned radio-frequency receiver, or in the preselector of a superheterodyne, it may be necessary to employ a coupled circuit pair that can be tuned over a fairly wide range, such as the broadcast band. If R_1 and R_2 are known for a number of points in the band, the value of v corresponding to the required band width can be calculated for each such point and (40) and (41) used to calculate the required value of s, and hence of u. However, it is not often that R_1 and R_2, including coil resistances and reflected resistances, are known with any accuracy over the band. They may, of course, be measured up, and the design procedure is then obvious, but an alternate experimental method will, in many cases, be more convenient. This method we shall now describe.

The two tuned circuits are temporarily coupled by a calibrated variable coupling impedance. This may be a small mutual inductance having a maximum value of about five microhenrys (for a broadcast band filter) or a variable condenser of good Q having a maximum capacitance of about 0.05 microfarad. The latter is perhaps not as convenient, unless a large air variable and a suitable assortment of fixed mica, or high grade paper, condensers are available. The value of coupling reactance, in ohms, required to give the necessary band width is experimentally determined for five or six frequencies within the tuning range to be covered. There then remains only the problem of choosing a coupling network which will give a curve of impedance versus frequency that will fit the experimental points. A method of doing this follows.

Let us suppose that the experimental curve of u vs. f is concave upward and is of such shape as to make likely the possibility of fitting it by using a coupling impedance consisting of a mutual inductance and a common condenser, the mutual inductance being so poled that its action aids that of the condenser. The total coupling reactance is

$$u = M\omega + 1/\omega C_m. \tag{43}$$

Let us introduce a radian velocity ω_a, as yet unspecified.

$$u = M\omega_a\left(\frac{\omega}{\omega_a} + \frac{\omega_a}{MC_m\omega\omega_a^2}\right) = M\omega_a\left(\gamma + \frac{1}{\gamma MC_m\omega_a^2}\right), \tag{44}$$

in which

$$\gamma = \frac{\omega}{\omega_a}.$$

Now choose ω_a so that

$$MC_m\omega_a^2 = 1. \tag{45}$$

Equation (45) then becomes

$$u/M\omega_a = \gamma + 1/\gamma. \tag{46}$$

For any given case, ω_a is a constant, and hence u is proportional to $\gamma + 1/\gamma$.

A plot of (46) is shown as curve I of Fig. 11. In order to fit the experimental curve to this figure, it is plotted on logarithmic paper of the same scale and laid on top of the curve representing (46). The upper sheet is then moved about, keeping the axes of the two sheets parallel, until the best possible fit is obtained between the experimental curve and curve I.

By way of illustration, let us suppose that when the above fit has been made the 1000-kilocycle abscissa on the experimental curve coincides with the abscissa at $\gamma=1.25$ on the lower sheet. Then $\omega_a=\omega/\gamma=800$ kilocycles. If at 1000 kilocycles the experimentally determined coupling impedance is 20 ohms, then we have from (46)

$$M\omega_a = \frac{u}{\gamma + 1/\gamma} = \frac{20}{1.25 + 0.8},$$

and, since ω_a is now known, M is easily calculated. Equation (45) will then give the required value of C_m. The complete coupling network is

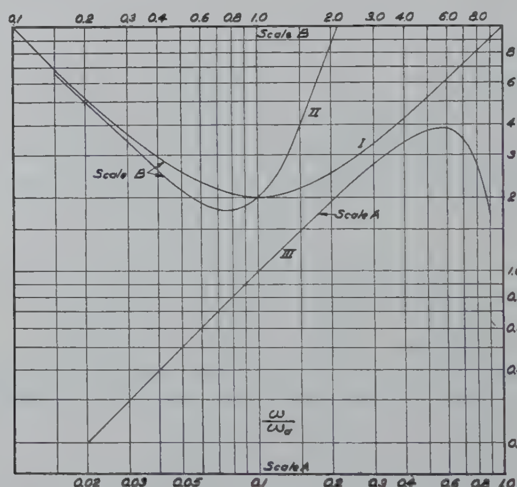


Fig. 11—Curves for computing the constants of a tunable filter of constant band width.

thus determined without cut-and-try adjustment of M and C_m, provided the experimental curve can be made to fit some portion of curve I.

If the desired fit cannot be obtained, it may be necessary to use some other form of coupling network. A coupling by means of a common condenser and a small condenser between the high sides of the circuits gives a more concave curve, which is shown by II in Fig. 11. For this case, we have

$$u = \frac{1}{\omega C_m} + \frac{C_h}{\omega C^2}, \tag{47}$$

since the high side capacitance of C_h is equivalent, at any frequency, to an added common capacitance C_h/C^2, C being practically equal to the tuning capacitance in one circuit.

Now,

$$C = 1/\omega^2 L$$

and hence,

$$u = \frac{1}{\omega C_m} + C_h \omega^3 L^2 = \frac{1}{\omega_a C_m}\left(\frac{\omega_a}{\omega} + C_m C_h L^2 \omega_a^4 \frac{\omega^3}{\omega_a^3}\right) \qquad (48)$$

$$u\omega_a C_m = \frac{1}{\gamma} + \gamma^3 C_m C_h L^2 \omega_a^4. \qquad (49)$$

Now define ω_a, for this case, by

$$C_m C_h L^2 \omega_a^4 = 1, \qquad (50)$$

whence,

$$u\omega_a C_m = \frac{1}{\gamma} + \gamma^3. \qquad (51)$$

A plot of this equation is shown by curve III of Fig. 11. If a fit with the experimental curve can be made, then ω_a is immediately determined, as before. The experimentally determined value of u corresponding to a certain value of γ will serve to determine C_m from (51), and C_h is determined from (50), since L is always known.

In some cases a curve of u vs. f which is concave downward is required. A fit may then be possible with a curve resulting from the combination of mutual inductance with high side capacitance, the two giving opposite coupling when the mutual inductance is poled oppositely to the case given in (43).

$$u = M\omega - C_h/\omega C^2, \qquad (52)$$

$$u = M\omega - \omega^3 L^2 C_h = M\omega_a\left(\frac{\omega}{\omega_a} - \frac{\omega^3 L^2}{\omega_a^3}\cdot\frac{\omega_a^2 C_h}{M}\right), \qquad (53)$$

$$\frac{u}{M\omega_a} = \gamma - \frac{\gamma^3 \omega_a^2 C_h L^2}{M}.$$

And defining ω_a by

$$\frac{\omega_a^2 C_h L^2}{M} = 1, \qquad (54)$$

we have,

$$\frac{u}{M\omega_a} = \gamma - \gamma^3. \qquad (55)$$

A plot of this equation is shown by curve III of Fig. 11. The method of determining the values of M and C_h should be obvious from what has gone before.

This general method of designing a constant band width filter has been tested in the laboratory, and is believed to be more convenient and rapid than any other which is commonly met.

Effects of Series Resistance and Shunt Resistance

It is evident from (16) and (19) that the shape of the secondary current curve is affected by the product of the resistances of the two circuits, and that an inequality of these resistances will cause no dissymmetry in the curve. This last is true only if the circuits are strictly isochronous, but when that is the case the addition of extra resistance to either circuit will decrease the secondary current but will not change the relative height of the two peaks.

When a resistance is connected in shunt to the secondary circuit, it can be considered as equivalent to a certain value of resistance in series with that circuit. To a first approximation, this series resistance can be regarded as constant, but if the filter is to be tuned over a considerable range, this equivalent resistance will, of course, vary considerably.

The total effective impedance of a resistance and reactance in parallel is

$$\frac{RX^2}{R^2 + X^2} + \frac{jXR^2}{R^2 + X^2}, \tag{56}$$

and in any given case this expression may be used to convert the condenser and shunt resistance to an equivalent condenser and series resistance that may be regarded as constant over a narrow frequency band. In practical applications of tuned circuits, the shunt resistance will be at least ten times the reactance of the condenser, and consequently (56) reduces to

$$\frac{X^2}{R} + jX. \tag{57}$$

The effective value of the capacity is then unaltered, and the equivalent series resistance is equal to the square of the condenser reactance divided by the shunt resistance.

Shift of Peaks With Variation of Common Reactance

The dependence of the frequencies at which the peaks occur upon the value of the common reactance is a matter of practical interest. A general idea of the way in which the peaks move may be had from qualitative considerations, but quantitative relations do not seem to have been formulated. Let us take as a reference value the total series

reactance of one circuit exclusive of X_m. Call this quantity X_a. Then,

$$X = X_a \pm X_m. \tag{58}$$

The sign to be used depends, of course, upon the nature of X_m.

$$v = \frac{X_a}{\sqrt{R_1R_2}} \pm \frac{X_m}{\sqrt{R_1R_2}}. \tag{59}$$

The value of v at which the peaks occur is given by (23), from which we have

$$X_{am} = \mp X_m \pm \sqrt{(M\omega \pm X_m)^2 - \frac{(R_1^2 + R_2^2)}{2}}. \tag{60}$$

The sign in the first ambiguity depends upon the nature of X_m, and is negative when X_m is inductive. The sign of the third is plus if M and X_m aid each other in increasing the coupling. The sign of the second depends upon which peak is being considered.

If L_a denotes the total inductance of one circuit exclusive of that in X_m and $f_a = 1/2\pi\sqrt{CL_a}$, we have

$$X_{am} = 2X_{La}\frac{(\Delta f_a)_m}{f_a} = 2\pi L_a(\Delta f_a)_m \tag{61}$$

$$(\Delta f_a)_m = \frac{1}{2\pi L_a}\left[\mp X_m \pm \sqrt{(M \pm X_m)^2 - \frac{(R_1^2 + R_2^2)}{2}}\right]. \tag{62}$$

If $X_m \neq 0$, the two peaks are symmetrical with respect to the resonant frequency f_a and move outward as M is increased.

If $M=0$, the peaks will be unsymmetrically located with respect to f_a and will move by different amounts when X_m is varied. The extreme case of $R_1 = R_2 = 0$ will illustrate this. Equation (62) then becomes

$$(\Delta f_a)_m = \frac{1}{2\pi L_a}(\mp X_m \pm \sqrt{X_m^2}) \tag{63}$$

and the peaks occur at

$$(\Delta f_a)_m = 0 \quad \text{and} \quad (\Delta f_a)_m = \mp \frac{X_m}{\pi L_a}. \tag{64}$$

If X_m is a pure inductive reactance the second peak occurs at

$$(\Delta f_a)_m = -f_a\frac{2L_m}{L_a}. \tag{65}$$

In the case just given, one peak stands still while the other keeps a distance from f_a that is directly proportional to X_m. When R_1 and R_2 are not zero but M is, one peak will move slightly and the other one more, as X_m is varied. In any case, the actual positions of the peaks and their dependence upon X_m can be readily calculated from (62).

Unequal L/C Ratios

When $L_1C_1 = L_2C_2$ but $L_1/C_1 \neq L_2C_2$, we may set

$$L_2 = \theta L_1, \quad C_2 = C_1/\theta. \tag{66}$$

Then,

$$X_2 = \theta X_1, \quad \text{and} \quad v_2 = \theta v_1. \tag{67}$$

Equation (12) may then be written

$$i_2 = \frac{u_0 e}{R_1R_2 - \theta X_1^2 + u_0^2 + j(R_1\theta X_1 + R_2X_1)}. \tag{68}$$

Rationalizing this, and introducing the abbreviations (14) and (16), we get

$$|i_2| = \frac{u_0 e}{R_1R_2\sqrt{(1+s^2-\theta v_1^2)^2 + \left[\theta v_1\sqrt{\frac{R_1}{R_2}} + v_1\sqrt{\frac{R_2}{R_1}}\right]^2}} \tag{69}$$

$$= \frac{u_0 e}{R_1R_2\sqrt{(1+s^2)^2 - 2\theta v_1^2\left(s^2 - \frac{\theta R_1}{2R_2} - \frac{R_2}{2\theta R_1}\right) + \theta^2 v_1^4}}. \tag{70}$$

Now let,

$$V = \theta v_1 \tag{71}$$

and,

$$B = \frac{\theta R_1}{R_2} + \frac{R_2}{\theta R_1}. \tag{72}$$

Then, introducing these, (70) becomes

$$y^2 = \frac{2s}{\sqrt{(1+s^2)^2 - 2V^2(s^2 - B/2) + V^4}} \tag{73}$$

which is of exactly the same form as (19), and hence the same families of resonance curves, Figs. 3, 4, 5, and 6, may be used for the study of isochronous circuits having unequal L/C ratios.

If, in addition to (66), we have $R_2=\theta R_1$, then $B=2$ and the circuits behave just as if they had equal inductances and equal resistances. If $R_2/R_1=L_2/L_1=\theta$, the two circuits have the same value of $Q=\omega L/R$.

When $\theta=1$, (73) of course reduces to (19), which is seen to be a special case of the general equation.

This analysis is of use where a transformer action is required of a pair of tuned coupled circuits.

Comparison with Selectivity of a Single Tuned Circuit

The relation between the selectivity of a single tuned circuit and of a pair each of which is identical with the single circuit is worth considering.

The current in a single circuit is

$$|i| = \frac{e}{\sqrt{R^2+X^2}} = \frac{e}{R\sqrt{1+v^2}}. \tag{74}$$

Define y in such manner as to make it readily comparable to y_2, but at the same time to give it a maximum value of unity.

$$y = \frac{R|i|}{e} \tag{75}$$

or,

$$y = \frac{1}{\sqrt{1+v^2}}. \tag{76}$$

Now let us note certain relations between y and y_2 when $b=2$.

When s is so small that $s^2 \ll 1$, (19) becomes

$$y_2 = \frac{2s}{\sqrt{1+2v^2+v^4}} = \frac{2s}{1+v^2}. \tag{77}$$

Consequently, $y_2 \sim y^2$ when the coupling is very loose. In other words, two loosely coupled identical circuits have exactly the same selectivity as two similar circuits separated by a unilateral amplifier.

When the coupling is increased, the selectivity of the coupled pair is reduced below that of two circuits separated by a tube. However, the shape of the over-all resonance curve well down from the top is the same in both cases, since for v sufficiently large $y_2 \sim 1/v^2$, while $y^2 \sim 1/v^2$ also. As the coupling is changed, the skirts of the curve are moved horizontally without a change of slope (on logarithmic paper).

We may also determine the point at which the resonance curve of a single circuit, or of a separated pair, intersects the curve of a coupled pair, assuming a maximum value of y, or y^2, or y_2 of unity in all cases.

For the single circuit curve, we determine the intersection with the coupled circuit curve by setting $y = y_2$ and solving for v. The result of this operation for $b = 2$ is

$$v^2 = 3s^2 - 1 \pm 2s\sqrt{2s^2 - 1}. \tag{78}$$

In determining the intersection of the curve for two separate circuits with that of a coupled pair, we set $y^2 = y_2$ and solve for v. The result for $b = 2$ is

$$v^2 = \frac{5s^2 - 1 \pm 2s\sqrt{s^4 + 4s^2 - 1}}{1 - 4s^2}. \tag{79}$$

Phase of Secondary Current

The vector expression for the secondary current is

$$i_2 = \frac{ju_0 e}{u_0^2 + R_1R_2 - X_1X_2 + j(R_1X_2 + R_2X_1)}. \tag{80}$$

Introducing the usual abbreviations and setting $X_1 = X_2$, this becomes

$$i_2 = \frac{\pm\, jse}{\sqrt{R_1R_2}\left[1 + s^2 - v^2 + jv\left(\sqrt{\frac{R_1}{R_2}} + \sqrt{\frac{R_2}{R_1}}\right)\right]}. \tag{81}$$

Now,

$$\sqrt{\frac{R_1}{R_2}} + \sqrt{\frac{R_2}{R_1}} = \sqrt{b + 2}. \tag{82}$$

Therefore,

$$\tan \phi_2 = \frac{-\, v\sqrt{b + 2}}{1 + s^2 - v^2}. \tag{83}$$

An interesting fact about this last expression is that, while the phase shift is in general dependent upon the ratio of resistances, a shift of 90 degrees from the value at $v = 0$ occurs when

$$v = \pm\sqrt{1 + s^2}, \tag{84}$$

and is therefore independent of b.

The total shift is $\phi_2 \pm 90$ degrees, depending upon the sign of the coupling reactance. A positive reactance results in a phase advance of 90 degrees, and vice versa.

In Fig. 12 is shown a family of curves of ϕ_2 versus v for $b = 2$ and for various values of s.

CURRENT IN PRIMARY CIRCUIT

From (10) and (11), we have

$$i_1 = \frac{Z_2}{Z_{12}} i_2. \tag{85}$$

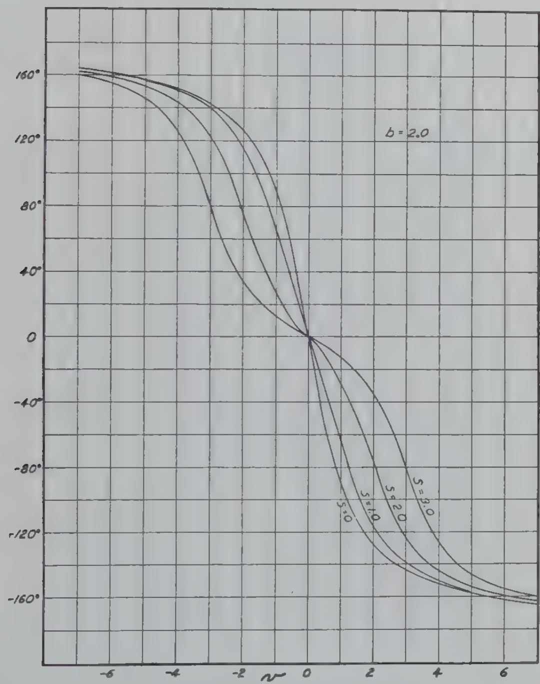


Fig. 12—Phase shift curves of the secondary current for the case of equal circuit resistances.

Since we are at present limiting our attention to the case of $Z_{12}=ju_0$, (85) gives

$$i_1 = \frac{-jZ_2 i_2}{u_0} \tag{86}$$

and,

$$y_1 = \frac{y_2}{u_0}\sqrt{R_2{}^2 + X^2} \tag{87}$$

in which,

$$y_1 = \frac{2\sqrt{R_1R_2}}{e} \left| i_1 \right|. \tag{88}$$

Equation (87) can be written

$$y_1 = \frac{y_2}{s}\sqrt{\frac{R_2}{R_1} + v^2}, \tag{89}$$

or,

$$y_1 \doteq \frac{2\sqrt{R_2/R_1 + v^2}}{\sqrt{(1+s^2)^2 - 2v^2\left(s^2 - \dfrac{b}{2}\right) + v^4}}. \tag{90}$$

This simple relation between primary and secondary current makes it easy to construct resonance curves of y_1 vs. v from those of y_2 vs. v

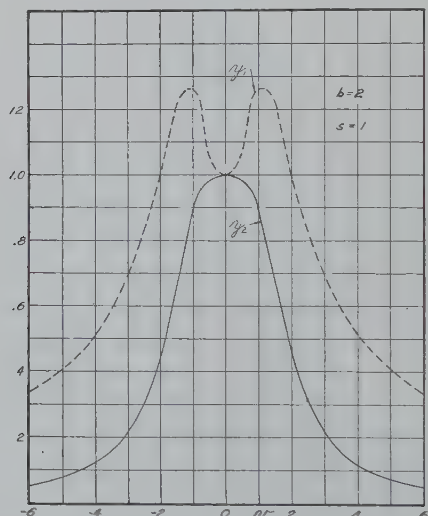


Fig. 13—Comparison of primary and secondary currents for the case of equal circuit resistances and critical coupling.

which have already been given. Plots of both primary and secondary current for $s=1.0$ are shown in Fig. 13 and for $s=2.0$ in Fig. 14. The circuit resistances are assumed to be equal in both cases. The high peaks and deep valleys of the primary current, even for $s=1.0$, stand in sharp contrast to the form of the secondary current.

The value of v which makes y_1 a maximum may be determined by differentiating (90) with respect to v, and setting the derivative equal to zero. On solving for v^2, the result is

$$v_{m1}^2 = -\frac{R_2}{R_1} + \sqrt{\frac{R_2^2}{R_1^2} + \frac{R_2}{R_1}(2s^2 - b) + (1+s^2)^2}. \tag{91}$$

If $R_1 = R_2$, this reduces to

$$v_{m1}^2 = -1 + s\sqrt{4 + s^2}. \tag{92}$$

The two peaks in the primary current will vanish when v_{m1}^2 reduces to zero. This will occur when

$$\frac{R_2}{R_1}(2s^2 - b) + (1 + s^2)^2 = 0,$$

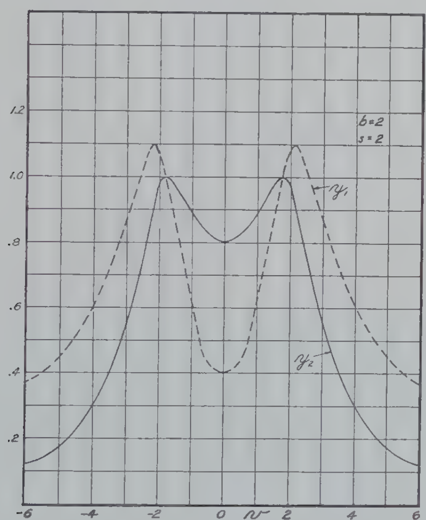


Fig. 14—Comparison of primary and secondary currents for the case of equal circuit resistances and coupling twice critical.

or,

$$s^2 = -\left(1 + \frac{R_2}{R_1}\right) + \sqrt{\frac{R_2}{R_1}(b + 2) + \frac{R_2^2}{R_1^2}}. \tag{93}$$

For $b = 2.0$, we have

$$s^2 = -2 + \sqrt{5}$$

or,

$$s = 0.487. \tag{94}$$

In order to get rid of peaks in the primary current, the coupling index must be reduced to less than one half the critical value for the secondary. When (94) is satisfied, y_1 will be more than double y_2.

An expression for the heights of the primary peaks may be obtained by substituting (91) into (90). The result is somewhat complicated, and will be given here only for $b=2$. It is

$$y_{1m} = \sqrt{\frac{2\sqrt{1+4/s^2}}{4 - s\sqrt{4+s^2} + s^2}}. \tag{95}$$

Another point to be noted is that when $b=2.0$ the curve of y_1 always passes through the peaks of y_2, when they exist. This can be proved by substituting (23) into (90). The result is identical with (29) when, and only when, $b=2.0$.

The height of the center of the y_1 curve is merely

$$y_{10} = \frac{y_{20}}{s}\sqrt{\frac{R_2}{R_1}} \tag{96}$$

or,

$$y_{10} = \frac{2}{1+s^2}\sqrt{\frac{R_2}{R_1}}. \tag{97}$$

When $s>1.0$, this height falls off more rapidly with increasing s than does that of y_2, as has already been noted.

Since the primary current is not usually of as much interest as is the secondary, it has not been given so detailed a treatment, but enough relations have been derived to make an extension of the analysis a simple matter. Equation (89) and the various curves of y_2 which have been given should be of particular use in this regard.

Impedance Across the Primary Circuit

In order to develop an expression for this quantity, let us imagine that the primary is connected in the plate circuit of a screen-grid tube, as in Fig. 1(b), and further that the internal plate resistance of this tube is extremely large. The plate current will then be $g_m e_g$ and will be independent of the impedance across the tuned circuit. This impedance, which we shall call Z_a, will be proportional to the voltage developed across the circuit, or

$$e_a = -Z_a i_p = -Z_a g_m e_g. \tag{98}$$

Since we are dealing with high Q circuits, the difference between $-Z_a i_p$ and $+ji_1/\omega C$ will be quite small, and may be neglected. Hence,

$$Z_a = \frac{-ji_1}{g_m e_g \omega C}. \tag{99}$$

The vector expression for i_1, which may be derived from (81), (82), and (86) is

$$i_1 = \frac{-e\left(\sqrt{\frac{R_2}{R_1}} + jv\right)}{\sqrt{R_1R_2}(1 + s^2 - v^2 + jv\sqrt{b+2}}. \tag{100}$$

From (1),

$$e = \frac{\mu e_g}{j\omega C r_p} = \frac{jg_m e_g}{\omega C}. \tag{101}$$

Hence,

$$Z_a = \frac{\sqrt{\frac{R_2}{R_1}} + jv}{\omega^2 C^2 \sqrt{R_1R_2}[1 + s^2 - v^2 + jv\sqrt{b+2}]}. \tag{102}$$

Also, from (88) and (99), we have

$$|Z_a| = \frac{y_1 e}{2g_m e_g \omega C\sqrt{R_1R_2}},$$

and, substituting (101), there results

$$|Z_a| = \frac{y_1}{2\omega^2 C^2\sqrt{R_1R_2}} = \frac{y_1 X_C{}^2}{2\sqrt{R_1R_2}}. \tag{103}$$

If we consider $X_C{}^2$ to be constant over the range of interest, then the impedance across the primary is directly proportional to y_1, and can be calculated from resonance curves of that quantity merely by multiplying by $X_C{}^2/2\sqrt{R_1R_2}$.

The impedance at $v=0$ is, from (102), simply

$$|Z_{a0}| = \frac{X_C{}^2}{R_1(1 + s^2)} \tag{104}$$

and steadily decreases as s increases. When $|Z_a|$ is small, the voltage developed across the primary is small, and hence the primary current will be small. The low value of $|Z_{a0}|$ which results when s is large goes with the small value of y_1 under the same conditions.

Equation (104) indicates that as $s \to \infty$, $|Z_{a0}| \to 0$. This value is not, of course, physically realizable, since s could approach infinity only if R_1 or R_2 approached zero.

Note on Gain and Signal-to-Noise Ratio as Compared With a Single Circuit

It is sometimes stated that the gain of a stage of high-frequency amplification is reduced by six decibels if a coupled circuit pair is used in place of a single tuned circuit. This is true if both circuits of the pair have a resistance equal to that of the single circuit. However, because of the resistance reflected into the primary, or into the single circuit, by the plate of the screen-grid tube, if often happens that the secondary has a lower resistance than the primary. Under such circumstances, the loss is not as much as six decibels, as will be readily shown.

If R_1 is the resistance of the single circuit and is also the resistance of the primary of the coupled pair, and R_2 is the resistance of the secondary, then the current in the single circuit will be e/R_1, while that in the secondary will be $e/2\sqrt{R_1R_2}$. The effective driving voltage e will be the same in both cases, and will be given by (1). Since the same condensers are used in both cases, it follows that the ratio of the output voltages will be

$$\frac{\text{output of coupled pair}}{\text{output of single circuit}} = \frac{1}{2}\sqrt{\frac{R_1}{R_2}}. \tag{105}$$

If the circuit resistances are equal, the loss is six decibels; if the primary resistance is twice that of the secondary, the loss is only three decibels; while if the primary has four times the loss of the secondary, the loss is zero decibels. This, of course, indicates a transformer action in the coupled circuit pair. In the case of a preselector, the effective resistance of the primary is generally higher than that of the secondary, because of the resistance reflected into the primary from the antenna circuit.

Corresponding to the misconception that the use of two circuits will reduce the gain six decibels, is the statement which is sometimes made that the use of a two-circuit preselector will reduce the signal-to-noise ratio of the receiver by a factor of two to one. This is never true, even when the circuit resistances are equal.

In order to compare the signal-to-noise ratios in the two cases, it will suffice to consider the case of critical coupling. The antiresonant resistance across the grid of the tube will be

$$\left| Z_{a1} \right| = X_c^2/R_1 \tag{106}$$

for the single circuit case.

Equation (104) was derived for the impedance across the primary. The impedance across the secondary will, of course, be the same, ex

cept that R_1 must be replaced by R_2. At critical coupling, the impedance across the tube in the two-circuit case will then be

$$|Z_{a2}| = X_c^2/2R_2. \tag{107}$$

Now, it is well established that the thermal noise applied to the grid of the tube is proportional to the square root of the resistance between the grid and cathode. Consequently, the ratio of noise in the two-circuit case to that in the one-circuit case will be

$$\frac{N_2}{N_1} = \sqrt{\frac{R_1}{2R_2}}. \tag{108}$$

Comparing this with the ratio of the output voltages, which has already been derived, it is evident that the signal-to-noise ratio will be reduced by a factor $1/\sqrt{2}$ when two circuits are used instead of one. This corresponds to a loss of three decibels and is independent of the ratio of the circuit resistances.

PART III

Circuits Not Strictly Isochronous

In most practical cases, we wish to have isochronous circuits, and the study of the effects of departure from syntonism is of interest in that it shows the troubles to which a filter may be subject by detuning. Intentionally detuned coupled circuits are not so likely to be used. Small amounts of detuning are therefore of greatest interest, and this is fortunate, since it enables us to use helpful approximations.

In developing this analysis, we shall continue to assume that the circuits are coupled by a pure reactance. In Part IV, the case of an impure coupling will be taken up, and we shall then consider that the circuits are isochronous. In order to be perfectly general, we should treat the case of nonisochronous circuits coupled by a complex impedance. This would, however, lead to great algebraic complexity and is entirely unnecessary from the standpoint of practical application. As long as the detuning is not very great, the effects of these two quantities may be studied separately and, when necessary, added together.

In studying the effects of detuning, we shall assume that

$$L_1 = L_2 = L, \quad \text{and} \quad C_1 \neq C_2. \tag{107}$$

These conditions are of common occurrence in practice, and happen to give a relatively simple mathematical treatment. Small inequalities in the inductances would not change the physical picture or the general character of the results obtained.

Referring to Fig. 15, the symbols have the following significance:

f_1 = the resonant frequency of the primary circuit; that is, the frequency at which the total reactance of L_1 and C_1 (which are defined in Part I) $=0$,

f_2 = the resonant frequency of the secondary circuit,

f_c = the frequency halfway between f_1 and f_2,

f = the independent variable,

$f_d = |f_c - f_1| = |f_c - f_2|$,

$\Delta f_1 = f - f_1$,

$\Delta f_2 = f - f_2$,

$\Delta f_2 = f - f_c$.

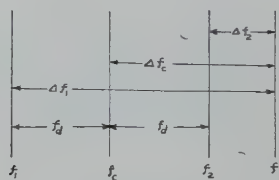


Fig. 15—Chart of the frequencies and frequency increments used in the analysis of detuned circuits.

From (20), we have

$$X_1 = 2\omega_1 L \frac{(f_d + \Delta f_c)}{f_1} = 2\omega_c L \frac{(f_d + \Delta f_c)}{f_c} = X_d + X_c \tag{109}$$

$$X_d = 2\omega_1 L \frac{f_d}{f_1} = 2\omega_c L \frac{f_d}{f_c} = 2\omega_2 L \frac{f_d}{f_2}. \tag{110}$$

X_d is the reactance of circuit 1 at the frequency f_c.

In a similar manner, we have

$$X_2 = 2\omega_2 L \frac{(\Delta f_c - f_d)}{f_2} = 2\omega_c L \frac{(\Delta f_c - f_d)}{f_c} = X_c - X_d. \tag{111}$$

With the help of (109) and (111), we can get rid of the two separate variables X_1 and X_2 and have only the single variable X_c, since X_d is a constant in any given case.

The expression for the secondary current is

$$|i_2| = \frac{u_0 e}{\sqrt{R_1^2 + x_1^2}\left[R_2^2 + \dfrac{2R_1R_2u_0^2}{R_1^2 + X_1^2} + \dfrac{R_1^2u_0^4}{(R_1^2 + X_1^2)^2} X_2^2 - \dfrac{2u_0^2X_1X_2}{R_1^2 + X_1^2} + \dfrac{u_0^4X_1^2}{(R_1^2 + X_1^2)^2}\right]^{1/2}}. \tag{112}$$

If we define v_1 and v_2 by

$$v_1 = X_1/\sqrt{R_1R_2}, \qquad v_2 = X_2/\sqrt{R_1R_2}, \tag{113}$$

and similarly,

$$v_d = X_d/\sqrt{R_1R_2} \quad \text{and} \quad v_c = X_c/\sqrt{R_1R_2}, \tag{114}$$

and taking s as defined by (14), we get as our expression for y_2

$$y_2 = \frac{2s}{\sqrt{(1+s^2)^2 + \dfrac{R_1}{R_2}v_2^2 + \dfrac{R_2}{R_1}v_1^2 - 2s^2v_1v_2 + v_1^2v_2^2}}. \tag{115}$$

If, now, we eliminate v_1 and v_2 with the help of (109), (111), and (114), there results

$$y_2 = \frac{2s}{\left[(1+s^2+v_d^2)^2 + v_d^2(b-2) + 2v_cv_d\left(\dfrac{R_2}{R_1} - \dfrac{R_1}{R_2}\right) - 2v_c^2\left(s^2+v_d^2-\dfrac{b}{2}\right) + v_c^4\right]^{1/2}}. \tag{116}$$

It will be noted that for the first time we have a term in the denominator which contains the first power of the independent variable. Consequently, the resonance curve will not, in general, be symmetrical, since this term will be of opposite sign on either side of the center frequency f_c. However, the dissymmetry can occur only if $R_1 \neq R_2$. If the circuit resistances are identical, detuning will not give unequal peaks nor in any way upset the symmetry of the resonance curve. On the other hand, if the resistances are unequal, very serious dissymmetry may result.

In Fig. 16 is shown the very great effect that detuning has upon the shape of the resonance curve when the ratio of resistances is nearly ten to one and the coupling is at the transitional value for the isochronous condition. It is interesting to note that, in addition to giving the curve a peculiar and unnatural shape, a small amount of detuning increases the maximum gain. This last is due to an approach, by the process of detuning, to the optimum resonance relation of Pierce.[7] When this relation is completely fulfilled, it is possible to obtain a value of unity for y_2 at one frequency, even though $R_1 \neq R_2$ and the circuits are not isochronous.

[7] G. W. Pierce, "Electric Oscillations and Electric Waves," Chap. XI, McGraw-Hill.

In Fig. 17 is shown the effect of detuning when b has the same value as before but s is increased to four. It will be noted that in the most extreme case one peak is considerably raised and the other lowered.

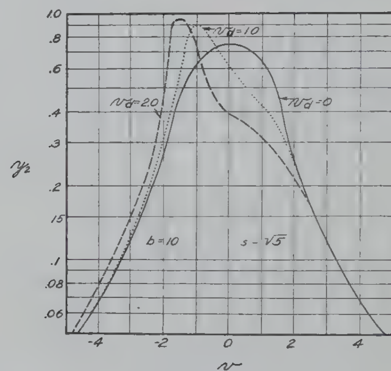


Fig. 16—Effect of detuning on the resonance curve of a pair of circuits having a resistance ratio of 9.19:1 and transitional coupling.

Were the direction of detuning of the secondary with respect to the primary to be reversed, the low-frequency peak would be depressed and the high-frequency peak raised. The opposite thing would happen if R_2/R_1 were replaced by R_1/R_2, and vice versa.

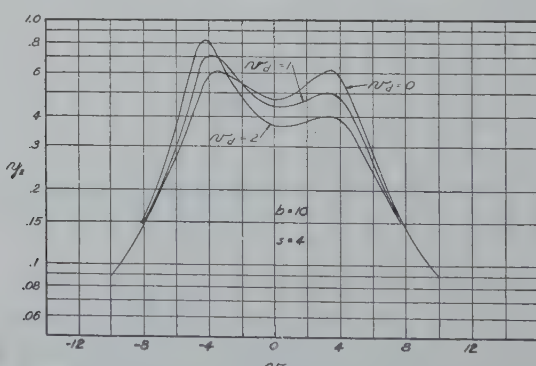


Fig. 17—Effect of detuning on a pair of circuits having a resistance ratio of 9.19:1 and a coupling index greater than the transitional value.

This may be made clearer by a summary showing the dependence of relative peak height on circuit relations. Thus,

	Frequency of Secondary Higher than Primary	Frequency of Secondary Lower than Primary
$R_2>R_1$	High-frequency peak depressed	Low-frequency peak depressed
$R_2<R_1$	Low-frequency peak depressed	High-frequency peak depressed

It is not necessary that the two circuits be so widely different in resistance in order to produce an appreciable amount of dissymmetry. In Fig. 18 are shown three curves for the case in which one circuit has a resistance only fifty per cent greater than that of the other, which gives a value to b of 2.167. This condition may easily occur in practice. The load thrown on the primary circuit by the plate resistance of the driving tube, or the load thrown on the secondary by the resistance of a diode detector, can cause inequalities in resistance of fifty per cent or often a good deal more.

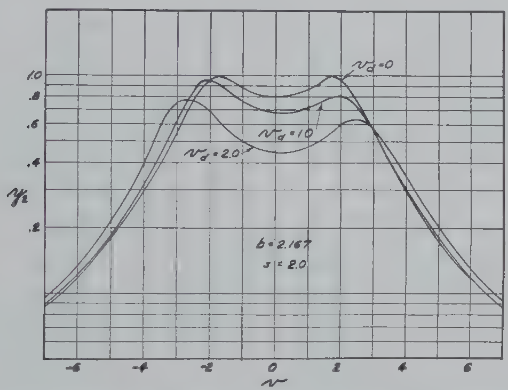


Fig. 18—Effect of detuning on a pair of circuits having a resistance ratio of only 1.5:1 and a coupling index twice the transitional value.

Case of Identical Resistances

When $R_1 = R_2$, (116) reduces to

$$y_2 = \frac{2s}{\sqrt{(1 + s^2 + v_d^2)^2 - 2v_c^2\left(s^2 + v_d^2 - \dfrac{b}{2}\right) + v_c^4}} \tag{117}$$

the demoninator of which is identical in form with that of (19). This is a fortunate result, since it enables us to use directly the resonance curves of Fig. 3. As far as the curve shape is concerned, the effect is the same as if the coupling index had been increased from a to $\sqrt{s^2+v_d^2}$. The actual magnitude of y_2 will not be correctly given by the curve sheets, but this is easily taken care of by sliding the whole curve in a vertical direction until the gain at $v=0$ is correct. This gain at the center is

$$y_{20} = \frac{2s}{1 + s^2 + v_d^2}. \tag{118}$$

In Fig. 19 are shown several curves of y_{20} vs. v_d, with s as parameter. It is evident that, while detuning can be used to increase the coupling effectively, the gain will always be less than would be the case if the coupling index were increased.

For a given value of v_d, the maximum value of y_{20} will occur when

$$s = \sqrt{1 + v_d^2}. \tag{119}$$

This defines a sort of generalized critical coupling, and reduces to $s=1$ when $v_d=0$.

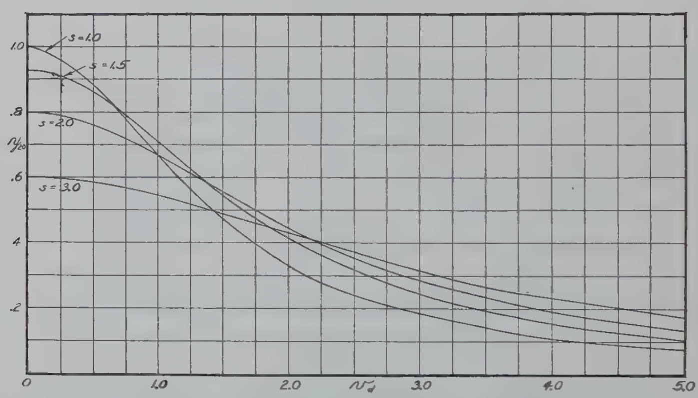


Fig. 19—Curves of gain at the center of the passed band versus the detuning parameter in the case of equal circuit resistances.

By analogy with the analysis of the isochronous case, it is evident that the values of v corresponding to the peaks of the resonance curve are

$$v_m = \pm \sqrt{s^2 + v_d^2 - 1}. \tag{120}$$

Transitional coupling occurs when

$$s = \sqrt{1 - v_d^2}, \tag{121}$$

and cannot be obtained if v_d is greater than 1. In other words, there will always be two peaks when the circuits are detuned enough to make v_d exceed unity, no matter how loose the coupling may be.

By analogy with (29), the value of y_2 at the peaks will be

$$y_{2m} = \frac{2s}{\sqrt{(1 + s^2 + v_d^2)^2 - (s^2 + v_d^2 - 1)^2}}, \tag{122}$$

which, when worked out, reduces to

$$y_{2m} = \frac{1}{\sqrt{1 + v_d^2/s^2}}. \tag{123}$$

From (118) and (123), it is evident that the ratio of peak to valley is given by

$$\frac{y_{2m}}{y_{20}} = \frac{1 + s^2 + v_d^2}{2\sqrt{s^2 + v_d^2}}. \tag{124}$$

Stagger Tuned Circuits

A well-known method of obtaining a band-pass filter characteristic is to use two tuned circuits separated from each other by a screen-grid tube, and to adjust the circuits to resonance at slightly different frequencies. The equations which have been developed are very convenient for the calculation of the over-all response of such a pair of circuits. All that is necessary is to set $s=0$, and to compute the shape of the resonance curve from the relation

$$y = \frac{2}{\left[(1 + v_d^2)^2 + v_d^2(b - 2) + 2v_c v_d\left(\frac{R_2}{R_1} - \frac{R_1}{R_2}\right) - 2v^2\left(v_d^2 - \frac{b}{2}\right) + v_c^4\right]^{1/2}}. \tag{125}$$

The correct gain can be obtained by computing its value at a single point, taking into account the tube constants, and then sliding the curve (on log paper) to fit this point.

If the two circuits are identical, (125) reduces to

$$y \doteq \frac{2}{\sqrt{(1 + v_d^2)^2 - 2v_d^2(v_d^2 - 1) + v_c^4}}, \tag{126}$$

and the resonance curves of Fig. 3 may be used to obtain the characteristic of the pair.

PART IV

Isochronous Circuits Coupled By A Complex Impedance

In this case, we cannot use ju_0 as the coupling impedance, but must use the complex form of Z_{12}. We can continue to assume that the reactive component of the coupling does not vary appreciably over the frequency range of interest, whence we have

$$Z_{12} = r + ju_0. \tag{127}$$

The expansion of (11) now becomes

$$i_2 = \frac{Z_{12}e}{R_1R_2 - X^2 - r^2 + u_0^2 + j(R_1X + R_2X - 2ru)}. \tag{128}$$

Now, define a new quantity

$$t = r/\sqrt{R_1R_2}. \tag{129}$$

Then, using the abbreviations which we have previously employed, (128) may be transformed into

$$y_2 = \frac{2\sqrt{s^2+t^2}}{\sqrt{(1+s^2-t^2)^2+4s^2t^2-4stv\sqrt{b+2}-2v^2\left(s^2-t^2-\frac{b}{2}\right)+v^4}}. \tag{130}$$

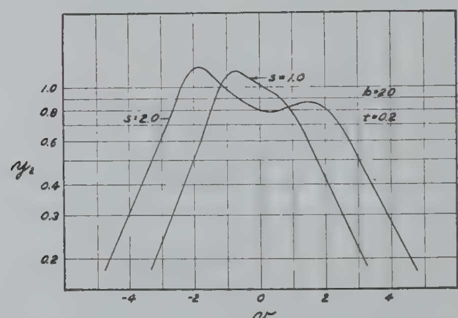


Fig. 20—Effect of resistance in the coupling impedance when the circuit resistances are equal.

Here again it is evident, from the form of the denominator, that the curve of y_2 vs. v will be unsymmetrical, since a term in the first power of v is present. However, this term will not vanish when $R_1 = R_2$, as was the case with detuning. An increase in b will tend to exaggerate the dissymmetry, since the term in v will be increased in magnitude, but the reduction of b to its lowest possible value of two will still leave a term of great importance.

In Fig. 20 are shown two curves for $t = 0.2$ and for two different values of s. These curves have been computed for the case of capacitance coupling, which makes u_0, and hence s, negative. If a common inductance were to be used as a coupling element, the high-frequency peak would be raised and the low-frequency peak depressed.

A point of interest is that the curves of y_2 are for the first time greater than utity. In the case of pure reactive coupling and isochronous circuits, the peaks of the resonance curves always had a value of unity, while the maximum value of the secondary current was

$e/2\sqrt{R_1R_2}$, and our physical intuition would lead us to expect that larger values of current were not possible under any circumstances.

This expectation is correct. The difficulty here is that, when t is increased, the total resistance around each circuit is also increased, since, as will be remembered, R_1 and R_2 both include the resistance of the coupling impedance, if any. Take for simplicity the case of $R_1 = R_2$. When t is 0.2, the R_1 and R_2, which enter into the definition of t, s, etc., are each increased by twenty-five per cent of the values which they they would have for $t=0$. There will always be a frequency at which currents can flow around the two circuits in series, without passing through the common impedance and without meeting any reactance. Under such circumstances, the current would encounter a reduced total resistance, and consequently could exceed the value $e/2R$. This is not quite an accurate picture, since the current leaving the primary would, of course, divide between the secondary and the coupling impedance, and our argument would be slightly modified. But the foregoing illustrates clearly why it is possible to obtain values of y_2 greater than unity when there is resistance in the coupling impedance.

Low Q Condenser Between High Potential Sides of Circuits

It was pointed out in Part I that if there is a large impedance Z_h between the high sides of the tuned circuits this can be replaced by an equivalent impedance Z_s in the common leg. Moreover if Z_h has a positive real part, Z_s will have a negative real part. Hence if the capacitance across the high sides has a low Q we shall effectively introduce a small negative resistance in the common leg of the two circuits. This will result in a change in the sign of the term in t in (130) and hence the low-frequency peak of the resonance curve will be depressed. This is just the reverse of the effect caused by a low Q in C_m.

Case of t^2 Small

Equation (130) is valid for any values of s and t, but in many practical instances t will be due entirely to a moderate loss in a coupling condenser, and will be rather small. Under such circumstances, it will be permissible to neglect t^2 entirely, whence (130) becomes

$$y_2 = \frac{2s}{\sqrt{(1+s^2)^2 - 4stv\sqrt{b+2} - 2v^2\left(s^2 - \frac{b}{2}\right) + v^4}}, \tag{131}$$

which is identical, except for the term in v, with the relation (19) that proved so useful in the case of pure reactance coupling. Let us rewrite (131) in the form

$$y_2 = \frac{2s}{\sqrt{(1+s^2)^2 - 2v^2\left(s^2 - \frac{b}{2}\right) + v^4}} \times \sqrt{1 - \frac{4s^2}{(1+s^2)^2 - 2v^2\left(s^2 - \frac{b}{2}\right) + v^4} \cdot \frac{tv\sqrt{b+2}}{s}}, \tag{132}$$

and, for the time being, denote by Y_2 the value of y_2 when $t=0$. Y_2 is, of course, the same as y_2 in Part II. Equation (132) can now be written

$$y_2 = \frac{Y_2}{\sqrt{1 - Y_2^2 \frac{tv}{s} \sqrt{b+2}}}. \tag{133}$$

With the help of this last relation, it is an easy matter to construct, from the charts of Figs. 3 to 6, resonance curves for a pair of circuits coupled by an impedance of reasonably small power factor. This may be done by assigning a value to v, picking the corresponding value of Y_2 from the proper chart, and substituting into (133).

Moderately small losses in the coupling impedance may well produce a considerable dissymmetry in the resonance curve. The more peaked the curve would be with $t=0$, the more effect a small value of t will have upon it. Thus, a little computation will show that if $|s| = 2.5$ and $t=0.05$, and $b=2$, the resulting resonance curve will have peaks which differ in magnitude by approximately one decibel. And yet this value of t corresponds to a Q for the coupling impedance of about fifty. Many paper condensers have Q's as low as this or lower, at radio frequencies.

Approximate Height of Resonance Peaks

In this part, and in Part III as well, the determination of the value of v which will make y_2 a maximum by straightforward differentiation leads to a cubic equation in v. The solution of this equation yields, in either case, results so complicated as to be of little value. However, in the case of an impure coupling impedance, with t reasonably small, we can get an approximate value of the peak heights from (131) or from (133) by assuming that the abscissas of the peaks are the same as they would be with $t=0$. These abscissas, which are given by (23), may be substituted into either of the expressions for y_2, and the heights of the two peaks, corresponding respectively to the positive and negative values of v, are then easily computed. In fact, a determination of the

peak heights by (133) and Figs. 3 to 6 will often suffice to show what a coupling impedance of known phase angle will do to the resonance curve of a filter.

Case of Pure Resistance Coupling

In this case, $s=0$, and (130) becomes

$$y_2 = \frac{2t}{\sqrt{(1-t^2)+2v^2\left(t^2+\frac{b}{2}\right)+v^4}}. \tag{134}$$

This equation contains only even powers of v, and hence the resonance curve must be symmetrical. Moreover, all of its terms are positive, since t is always less than unity, and therefore the curve can never have more than one peak, a result already well known.

It will be noted that when $v=0$, it is possible for y_2 to be greater than unity. The reason for this has already been explained.

If t is quite small, (134) reduces to

$$y_2 = \frac{2t}{\sqrt{1+bv^2+v^4}}. \tag{135}$$

In the case of pure reactive coupling, we have, when s is quite small,

$$y_2 = \frac{2s}{\sqrt{1+bv^2+v^4}}, \tag{136}$$

which is of exactly the same form as (135). Moreover, the denominator of (130) will reduce to the same form when s^2 and t^2 are neglected. Hence, we have the interesting result that when two circuits are loosely coupled, the form and amplitude of the secondary current resonance curve will depend only upon the magnitude of the coupling impedance and not at all upon its phase angle. This is, of course, in sharp contrast to the conditions which exist with tighter coupling.

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BOOK REVIEW

"Handbook of Chemistry and Physics. A Ready-Reference Book of Chemical and Physical Data," twenty-first edition, Charles D. Hodgman, Editor-in-Chief, 2023 pages. Chemical Rubber Publishing Co., Cleveland, Ohio. Price $6.00.

This handbook is so well and favorably known that a notice of the twenty-first edition need concern itself only with the changes and additions that have been made.

In the first section—Mathematical Tables—the order of the material has been altered from an alphabetical arrangement to one based on purpose. Thus the tables come first and the mathematical formulas last. There has been considerable material on statistical mathematics added; the numerical tables have been much enlarged, and an entirely new table of haversines added.

In the second section—Properties and Physical Constants—the table of isotopes has been revised and brought up to date, and in addition a most valuable table giving a large number of properties of commercially obtainable plastics has been added.

In the third section no new topics have been added and it remains practically identical with the same section of the twentieth edition. The fourth section also remains much as before, the only addition of note being a table to facilitate the reduction of gas volumes to standard conditions of temperature and pressure.

In the fifth section, the part on laboratory arts and recipes has been much enlarged and enriched, as has also the part on photographic formulas. In addition, an entirely new table of the acceleration due to gravity, latitude, longitude, and elevation has been added.

These additions have increased the number of pages by 72, the volume now attaining a rather unwieldy bulk due to its upward of 2000 pages. At the present rate of growth, it would seem that before long the editors would have to consider the advisability of issuing the handbook in two or more volumes if its usefulness is to continue unimpaired. Indeed, in the present edition the book is so bulky and the inside margins are so narrow that it is in many places difficult to read the data on the inside columns. In view of the great usefulness of the handbook, the reviewer trusts that the editors will give careful consideration to this feature of convenience in use in planning further editions.

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